University of Alberta

Diamond Mine Reclamation in the NWT: Substrates, Soil Amendments and Native Plant Community Development

by

Bonnie Leanne Kwiatkowski ©

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ABSTRACT

With diamond mining intensifying in the Canadian north, the diamond industry has the challenge to develop reclamation practices, returning the disturbance to pre-mine conditions. Waste materials produced from mining processes are low in organic matter and nutrients, coarse textured and not conducive for plant establishment. To ameliorate these conditions and facilitate vegetation establishment, five substrates, five soil amendments, six seed mixes and two seeding seasons were evaluated. Substrates included, glacial till (Till), processed kimberlite (PK), 50% PK / 50% Till, 25% PK / 75% Till and gravel. Amendments included topsoil, sewage sludge, fertilizer, sludge from a water treatment facility and no amendment. Seed mixes included combinations of eleven native grasses and six native forbs. Substrate properties, including texture, cation exchange capacity, nutrient availability and organic carbon were significantly improved by Till and PK combinations and amendment additions. Plant growth was significantly greater with addition of nutrient and structure improving amendments.

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CHAPTER I. INTRODUCTION

1.0 BACKGROUND

1.1 Diamond Mining

Diamonds are currently being mined in about 25 countries, on every continent except Europe and Antarctica (Hart 2001). Kimberlite pipes, which are carrot shaped pipes that represent the roots of ancient small volcanoes, bring diamonds to the surface of the earth and make them accessible for mining. These pipes are found in the oldest portions of the continents, where the basement rocks are older than 1.5 billion years, hence their presence in the Canadian Shield. Kimberlites are complex and geochemically variable, hybrid, ultrabasic, intrusive but volcanic-like rocks that typically contain xenocrysts and megacrysts (predominantly of olivine) set in a fine grained matrix of olivine, serpentine, carbonate and other minerals (Baker et al. 2001). Diamondiferous kimberlite pipes are a rarity, for although the world has a known population of some six thousand pipes, only a few dozen have valuable diamonds.

Mining of a diamond bearing kimberlite pipe starts with the excavation of a pit into the pipe. In this open pit process, hard rock is drilled and blasted with explosives and the rock and ore material is removed for processing with large excavators and haul trucks. As open pit mining deepens, the mining goes underground with vertical shafts descending to horizontal passageways that enter the pipe.

Diamond ore processing does not require chemicals to separate the diamonds from the kimberlite. Processing uses gravity based methods, which rely on the diamonds' heavier weight to separate them from much of the waste kimberlite (Diavk 2005). Due to the nature of the mining process, there are large amounts of waste materials. The primary waste products, glacial till and processed kimberlite tailings, are either stock piled or held in containment facilities in preparation for the eventual closure of the mine.

1.2 Diamond Mining In The Canadian Arctic

Diamond bearing kimberlite pipes were first discovered in Canada's Northwest Territories (NWT) in 1991 in the Lac de Gras area of the Slave Geological Province (Levinson and Kjarsgaard 2001). There have since been several major developments with the Ekati mine starting production in 1998, and the Diavik project commencing in 2003. The Jerico and Snap Lake projects are currently in the construction phase of development and at least 250 additional occurrences of kimberlite, many with economic potential, have been discovered in the Slave Geological Province. Once all four of these mines are in full production, Canada's contribution to the world supply of rough diamonds could be approximately 10% by weight and 15% by value (Levinson and Kjarsgaard 2001).

Diavik Diamond Mine Inc. (Diavik), currently one of the companies mining for diamonds in the NWT, is operating a diamond mine on East Island of Lac de Gras. Diavik's ore bodies, dated at approximately 55 million years, are surrounded by ancient Precambrian granites and metamorphosed sedimentary rocks that are approximately 2.7 billion years old (Diavk 2002). Under the current mine plan, Diavik expects to mine three diamond bearing kimberlite pipes which are located beneath the waters of Lac de Gras, just offshore East Island. To mine the ore bodies Diavik constructed a dike in 2002 to allow the overlying waters of Lac de Gras to be removed temporarily. The physical plant is located on East Island and includes a kimberlite processing plant, accommodation complex, maintenance shop, diesel fuel storage tanks, boiler house, sewage treatment plant, powerhouse, potable water treatment plant and wastewater treatment plant.

As a pioneer in the diamond industry in Canada, Diavik has the challenge to successfully reclaim mining and the opportunity to develop innovative, cost effective and environmentally sustainable methods to achieve this goal.

1.3 Diamond Mine Reclamation In The Arctic

Human induced disturbances in the arctic often cause long lasting changes in tundra landscapes (Truett and Kertell 1992), therefore reclamation is essential to restore ecosystem function and integrity. The land surface associated with diamond mining is typically waste rock, or tailings waste, which possess few physical and chemical characteristics favorable for plant establishment and growth. Successful reclamation involves the re-establishment of soil processes and native plant communities on gravel roads and pads, waste rock and till stockpiles and processed kimberlite containment facilities.

In the NWT the federal government, through the Department of Indian Affairs and Northern Development (DIAND), is responsible for the management of water, hydrocarbons and mineral resources as well as the administration of most crown land. The Canada Mining Regulations, under the Territorial Lands Act, provide control over mineral rights on crown land and payment of royalties to the crown (Government of Canada 2006). However, it is the NWT government that has jurisdiction over many of the areas that affect mining, including the environment. Permitting and licensing of mineral development projects are subject to the Mackenzie Valley Resource Management Act which is related to the NWT Lands Act and the NWT Waters Act.

The abandonment and restoration plan for the Diavik project was developed in accordance with regulatory guidelines provided by the government of the NWT and DIAND. The overall approach to abandonment and reclamation planning for the mine conforms to established international guidelines for mine reclamation and closure, and is based upon the philosophy of applying best practices appropriate to operations and environmental management under northern conditions.

2.0 LITERATURE REVIEW

2.1 Arctic Tundra Environment

The Arctic, which includes most of Alaska, the Yukon, the Northwest Territories, Greenland, northern Scandinavia, Siberia and the Arctic Ocean, is a fragile component of the global earth system (Reynonds and Tenhunen 1996). In the Northwest Territories, the arctic is divided into the Arctic Cordillera, the Northern and Southern Arctic, the Taiga Plains and the Taiga Shield ecozones.

The Southern Arctic Ecozone, where Diavik is located (approximately 200 km south of the arctic circle), is characterized by sprawling shrub lands, wet sedge meadows and cold, clear lakes (Environment Canada 2006). Summers are short (about four months), cool and moist; winters are long and extremely cold. Total annual precipitation is usually less than 250 mm in the west and rarely more than 500 mm in the east. This ecozone is bounded to the south by the treeline, a broad ecological division between the taiga forest and the treeless arctic tundra. Permafrost, low precipitation, low atmospheric moisture content, continuous blowing of cold, dry winds and extremely low winter temperatures are among the factors that limit plant growth in this ecozone (Environment Canada 2006). In most areas of the Arctic, less than ten species of higher plants make up more than 90% of the vascular plant biomass (Chapin and Korner 1995). As few as 20 genera account for most of the vascular plant biomass of the circumpolar Arctic (e.g. shrubs of the genera *Betula* (L.) (Birch), *Rubus* (L.) (Blackberry), *Dryas* (L.) (Mountain-avens), *Vaccinium* (L.) (Blueberry), *Empetrum* (L.) (Crowberry) and *Ledum* (L.) (Labrador tea), and the sedges *Eriophorum* (L.) (Cottongrass) and *Carex* (L.) (Sedge species)).

One of the most important physical characteristics which differentiates the Arctic from temperate regions is the presence of permafrost (Hernandez 1973). The polar air mass responsible for the Arctic climate is cold, due to low annual radiation input. This results in negative mean annual air temperature and therefore the presence of permafrost (Chapin and Shaver 1985). Permafrost occurs continuously throughout the Southern Arctic Ecozone; sometimes only centimeters below the surface, it acts like a dam that stops the downward movement of water. Consequently, even though there is very little precipitation in the region, the soils are often waterlogged or frozen. Repeated freezing and thawing of these soils creates patterned ground-polygons, earth hummocks and mud boils on the surface. Intense frost heaving often splits apart the underlying bedrock and forces large angular boulders to the surface. In areas of permafrost with excess ice, disturbance of the tundra surface, such as the killing of vegetation without removal of material, peeling off of the turf, or compaction of peaty ground, raises the mean summer ground surface temperature, which in turn can increases summer thaw depth and thermokarst (McKendrick 1991).

Thermokarst is melting of excess ice which results in surface subsidence. Thermal subsidence depends upon heat conduction, for example, from a pool of water directly overlying icy soil, or from conduction through an intervening layer of unfrozen soil (MacKay 1970). Thermokarst subsidence is associated with the thawing of soils containing excess ice as heat is conducted through the disturbed active layer (MacKay 1970). When the ground surface is disturbed, the active layer deepens and the permafrost degrades. If the newly thawed permafrost is supersaturated with ice (water), the excess water will be released and the ground will subside. In the short term subsidence is permanent and irreversible. When the time span is lengthened to permit revegetation, the active layer will eventually thin and permafrost will return (MacKay 1970).

The arid environment in the Southern Arctic Ecozone results in low soil moisture on elevated surfaces (Jorgenson and Joyce 1994). Low soil moisture not only limits plant growth and seed germination but also reduces nutrient availability by reducing nutrient movement through the soil. Although most nutrients in arctic soils are sufficient for plant needs, many factors including low soil temperatures and permafrost have made much of the arctic phosphorus and nitrogen deficient (Truett and Kertell 1992).

Low temperatures inhibit chemical weathering, biological decomposition and along with poor aeration, reduce rates of nutrient release from soil organic matter and minimize nitrogen fixation rates. Nutrient inputs from precipitation are an order of magnitude lower in the Arctic than in temperate systems because low temperatures limit the quantity of precipitation and the nutrients contained therein (Chapin 1983, Crawford 1989). Nutrients are tied up in organic matter, which is buried below permafrost before decomposition, and therefore efficient nutrient cycling does not occur without thermokarst and the nutrients remain unavailable to plants. Studies have shown that growth of tundra plants is constrained by deficiencies in soil phosphorus, soil nitrogen or both (Truett and Kertell 1992).

The physical environment controls most plant growth and establishment in the Arctic (Billings 1987). Certain biological factors are important locally and with some species, but are insignific[illegible] when compared to the severity of wind, snow and low temperatures of the atmosphere and soil. Most physiological processes of arctic plants are less temperature sensitive than those of temperate counterparts and consequently are most strongly limited by factors other than temperature (Chapin 1983). Environmental constraints on the development of arctic vegetation interact with genetic and evolutionary constraints unique to those flora in the cold summer climates north of the treeline.

Vegetation in the Arctic, being diminutive, can do little to protect itself from severe winds through the development of complex multilayered communities as in temperate climates (Crawford 1989). Microtopography therefore has a very marked influence on the pattern of vegetation development in arctic habitats. Wind exposure results in thin snow cover, low soil water and reduced temperatures during the growing season. These adversities are heightened by the wind removing plant litter and thus depleting the system of nutrients.

Research has shown that arctic plants are extremely well adapted to low temperatures and other factors such as short growing seasons, low nutrient availability due to slow decomposition and restricted drainage and poor aeration caused by permafrost, primarily limit plant growth and reproduction (Chapin and Shaver 1985, Jorgenson and Joyce 1994). Arctic plants are adapted to metabolizing, growing and reproducing at low temperatures, not far above the freezing mark (Crawford 1989). The 24 hour photoperiod of the arctic summer, from snowmelt until late July or mid August, compensates for the low radiation intensity, so that the daily total radiation input in July is similar in arctic and temperate regions (Chapin and Shaver 1985). Winter snow cover provides benefits to plants by providing thermal insulation, reducing exposure to low temperature extremes and fluctuating temperatures, allowing plants to emerge from the snow primed to initiate growth (Bilbrough et al. 2000).

Photosynthesis by arctic plants is limited less by air temperature than by date of snowmelt, light intensity and rate of production of leaf area (Chapin 1983). The optimum temperature for photosynthesis in arctic plants is generally about 15 °C, compared to a 25 °C temperature optimum for temperate plants. Photosynthetic rate of arctic plants varies by species and is relatively insensitive to reductions in air temperature below optimum, so that substantial rates can be maintained even at 0 °C (Chapin 1983).

Arctic plants are low in stature, ranging from low shrubs to crustose lichens to avoid strong and chilling winds. They photosynthesize by the C_3 pathway. Most biotic activity in the Arctic occurs in a narrow band from 5 cm below to 10 cm above the soil surface (Chapin and Shaver 1985). The most abundant and dominant growth form in the Arctic is the long lived perennial herb especially of the graminoid type, sedges and grasses. Most of these perennials, both dicotyledons and monocotyledons, have large underground root and rhizome systems in which carbohydrates and other compounds are stored (Billings 1987, Murray 1995).

Arctic perennial plants are slow growing and often take several years to reach the flowering stage. Most species reproduce by seeds, however many plants have responded to the short growing season by increasing vegetative reproduction and have the ability to also reproduce by rhizomes and/or stolons (Billings 1987, Murray 1995). Seeds of many species can remain frozen and buried under peat for years and then germinate when exposed to light and temperatures above freezing.

Arctic plants, although small in size, vary in both above and below ground morphology (Crawford 1989). The sparse nature of plant cover does not allow the vegetation to significantly alter the environment in its own favor. Consequently, the only change that is provided in the habitat comes from topographical and microclimate differences. Variations in plant form expose different tissues to varying degrees of climatic stress and are consequently very closely related to small changes in topography and microclimate.

2.2 Succession In The Arctic

Odum (1971) defined succession as ecosystem development which involves changes in species structure, is reasonably directional and therefore predictable, is community controlled (even though the physical environment determines the pattern, the rate of change, and often sets the limit as to how far development can go) and culminates in a stabilized ecosystem. Succession refers to changes in species composition and abundance during or following a disturbance (Cargill and Chapin 1987). Disturbance is a change in vegetation or underlying substrate caused by some external factor (Walker 1996). In general, two major kinds of vegetation changes, primary and secondary, are distinguished in the concept of succession. Primary succession refers to the plant community formation process that begins on substrates that had never before supported vegetation (e.g. following severe disturbance); secondary succession occurs on disturbed areas that have remnants of previous vegetation (Mueller-Dombois and Ellenberg 1974). Primary succession must rely on colonizing plants, whereas secondary succession relies on existing viable seeds and vegetative propagules.

Plant community succession in the Arctic is a long process that can still be in the early stages even many decades after a disturbance (Harper and Kershaw 1996). Colonizers capture snow, shade the soil, add litter to the surface and roots to the subsurface. Seral communities modify the environment, making it more suitable for successors, which eventually replace the initial colonizers (McKendrick et al. 1997).

Mosses invade and build a layer of peat that insulates the soil, elevates soil moisture and reduces thickness of the annual thaw to less than 50 cm. Ice lenses and wedges form in the soil, and polygon patterns predominate the land surface. Eventually the environment changes so drastically that few of the original vascular plant species are able to survive (McKendrick et al. 1997).

The pattern of succession in arctic environments is largely determined by species life history traits (Cargill and Chapin 1987). The community present on a site at any point in time and the patterns of change are affected by many factors. These factors include 1) life history characteristics of each species, such as dispersal abilities, growth rates, life span and reproductive behavior 2) physiological attributes of individual species, such as tolerance to low levels of nutrients, light or water 3) ways in which each species modifies the habitat by shading, nutrient and water consumption, deposition of litter, etc. and 4) interactions which determine the competitive and/or mutualistic relationships among species (Cargill and Chapin 1987).

Succession can be slow and ecosystem development poor on disturbed mine soils because they generally provide suboptimal conditions for plant establishment and growth (Smyth 1997). Xeric sites such as roads, camp pads and storage pads are often coarse textured resulting in low moisture availability, deficiencies in plant available nutrients, low organic matter and very few buried seeds or vegetative propagules. Recovery of these sites represents a succession process which can resemble primary succession after a natural disturbance on glacial till (Cargill and Chapin 1987). Mine soils resemble soils exposed by the retreat of glaciers and contain very little nitrogen, so species with nitrogen fixing symbionts are important early colonizers, leading to a buildup of soil nitrogen and subsequent community development. Early colonizers include species with light weight seeds (e.g. *Salix alaxensis* ((Anderss.) Coville) (Alaska willow), *Salix glauca* (L.) (Grey leaved willow) and *Epilobium latifolium* (L.) (Broad leaved willowherb)) and legumes whose seeds are probably carried by wind and water from surrounding areas (*Astragalus alpinus* (L.) (Alpine milkvetch), *Oxytropis maydelliana* (Trautv) (Maydell's oxytrope) and *Hedysarum mackenzii* (Rich.) (Northern hedysarum)). These species are relatively short lived and are eventually replaced by long lived species such as *Dryas integrifolia* (Vahl) (Entire leaf mountain avens) and *Carex aquatilis* (Wahlenb.) (Water sedge). Many of these early successional species facilitate establishment of later species by stabilization of substrate, and in the case of legumes, by symbiotic nitrogen fixation (Cargill and Chapin 1987).

Grasses influence the environment differently than forbs, legumes and shrubs in several ways, including the live canopy and very dense shallow root system of planted grass, and the higher moss cover, particularly in early successional seres (Densmore 1992). Grass utilize soil moisture in upper portions of the soil profile. A drier, hotter soil surface layer decreases the number of microsites for seedling establishment. Moss also contributes to the loss of microsites because it dries out much more rapidly than mineral soil, and dry moss in full sunlight can quickly reach temperatures lethal to seedlings (Densmore 1992, McKendrick et al. 1997). Species with small seeds such as *Epilobium latifolium* have great difficulty establishing on dry sites. Smaller seeds are more affected by surface dryness than larger seeds because larger seeds have reserves for more rapid root elongation below the drying surface layer (Densmore 1992).

In marginal environments, adaptations of native plant species to the adverse growing conditions offer many advantages for revegetation efforts (Brown et al. 1978, Densmore 1992, Smyth 1997) and that seeded, non native species are often eliminated from disturbed sites prior to replacement by native species. Establishing dense stands of certain grass species quickly on barren sites is opposite to the way natural sequence of plant species changes in tundra communities (McKendrick 1997a). Where dense stands of aggressive grasses have established, there is little space for other plants to invade. Densmore (1992) found a grass seeded treatment (*Festuca rubra* (L.) (Red fescue), *Poa pretensis* (L.) (Kentucky bluegrass), *Alopecurus pratensis* (L.) (Meadow foxtail), *Agrostis alba* (auct. non L.) (Redtop) and *Lolium mulitflorum*(Lam.) (Italian ryegrass)) decreased the rate and altered the pattern of succession compared to an unseeded treatment during the same time period by inhibiting the establishment of native species. *Epilobium latifolium* which is a native nonleguminous forb, failed to establish on the grass treatment, but was abundant and provided substantial cover in the unseeded treatment. In contrast, *Astralagus alpinus* (Alpine milkvetch), which is a native legume, was not affected by the grass treatment.

Seeding of native grass species to reduce erosion in areas with high winds can be beneficial for reclamation where there is no buried seed bank (Cargill and Chapin 1987). Native species are usually preferred, or even required, for reclamation since they are well adapted to arctic conditions and minimize the potential for ecological problems (Johnson 1987). They may also be preferable for native wildlife forage or habitat. Unfortunately, native plants and seeds are usually in short supply. There are relatively few commercial seed producers in Alaska or northern Canada to provide native seed for reclamation projects in the Arctic. Long lead times, uncertain climatic conditions and even small seed size, as in *Calamagrostis canadensis* ((Michx) Beauv.) (Bluejoint), can impede native seed production (Johnson 1987).

2.3 Climate Change In The Arctic

Global circulation models used to examine the effects of anthropogenically enhanced concentrations of greenhouse gases in the atmosphere all indicate that warming will occur first and with greatest intensity at high latitudes (Maxwell 1992). This will be the result of positive feedbacks, especially lower albedos with a longer snow-free season and reduced sea ice cover. The potential long term consequences for the Arctic are enormous, including melting permafrost, deepening the active layer, causing thermokarst erosion, increased release of CO_2 and CH_4 from buried/frozen organic deposits and reorganization of arctic ecosystems by changing dominance of existing species (Henry and Molau 1997). Over the short term (10 to 30 years) the climate is likely to be much more variable in the High Arctic, with increased frequency of extreme weather such as increased snow fall and icing events in autumn and spring, and cloudy summers with increased precipitation.

Warmer, longer growing seasons will affect tundra plants and ecosystems both directly and indirectly (Henry and Molau 1997). Many species will shift phenology, flowering earlier in the season, and grow at increased rates. Arctic plant species respond individually to environmental changes in temperature, nutrients and light which can result in reorganization of arctic plant communities. These changes could potentially change interpretations of the current reclamation scenario in the Arctic.

2.4 Reclamation In The Arctic

2.4.1 Challenges due to mining operations

In the Arctic, even subtle changes in air temperature, radiation, atmospheric and oceanic chemistry and ocean heat transport are likely to have large effects on sea ice, snow, glaciers, permafrost and tundra ecosystems (Reynolds and Tenhunen 1996). Large scale disturbances, such as mining operations, can result in altered thermal, hydrological or nutrient regimes, as well as in changes in species composition, vegetation structure or primary production (Walker 1996).

To prevent thawing of the underlying permafrost and to provide a stable surface for development, gravel pads are essential to the development of arctic diamond mine operations and account for much of the land affected by development (Jorgenson and Joyce 1994). Gravel pads, generally 1.5 m thick or greater, are necessary for roads, storage pads, facilities and airstrips. Although gravel pads prevent thawing of the underlying permafrost, they cause other environmental impacts including creation of dry, elevated sites that are difficult to revegetate, blockage of natural drainage patterns and alteration of snow drift patterns (Chambers 1995a, Walker 1996). Gravel pads located in the wet tundra offer an environment much drier and less protected from wind than the undisturbed surroundings. Consequently, plants adapted to successfully invading these pads would most likely come from the most exposed and driest habitats which are often uncommon or relatively small components of the landscape near the disturbance (McKendrick 1987). This limits the availability of plant propagules of pioneering species adapted to the gravel pad environments, and thus can delay natural biological community succession.

Gravel pad thickness is an important consideration in revegetation. Plant cover is inversely related to fill thickness; it is very low on sites with more than 1 m of gravel (Walker 1996, Streever 2001). Thick gravel pads are the most difficult to revegetate because the surface is low in moisture, nutrients and organic matter due to the physical and chemical properties of the substrate, limited dispersal of native propagules and because the surface of the pad receives very little ground water input (Jorgenson and Joyce 1994, Bishop and Chapin 1989). Gravel removal is becoming an increasingly common practice, because it facilitates revegetation and allows reuse of gravel at other locations. However, removal of gravel often leads to increased thaw depths and thermokarst (Streever 2001, MacKay 1970).

To improve arid conditions on raised gravel surfaces a variety of hydrological manipulations can be incorporated into the reclamation plan including creation of gravel berms to capture drifting snow to increase water input to the soil and adding organic matter and/or amendments to improve water-holding capacity and reduce evaporation (Jorgenson and Joyce 1994). Techniques for improving soil structure and nutrient availability include application of fine-grained substrates, organic topsoil and sewage sludge and the use of nitrogen-fixing legumes. With sufficient site preparation and appropriate species selection, productive and self sustaining plant communities that are useful to a range of wildlife species can be established (Jorgenson and Joyce 1994).

2.4.2 Site preparation and soil reconstruction

Site preparation involves contouring the disturbed area in a manner that promotes surface stabilization, erosion control and drainage while also advancing the state of the reclamation goals and predisturbance site characteristics. Gravel pads constructed during mining operations are generally very compact due to heavy equipment, thereby forming a physical barrier to root penetration and reducing water holding capacity in the soil (Johnson 1987). Vegetation performance can be considerably hindered if compaction remains under reclamation substrates (Moffat and Bending 2000). Gravel pads need to be scarified to alleviate compaction to maximize vegetation performance, however, this can increase soil temperatures, depth of thaw and initiate thermokarst (Chapin and Shaver 1981, Streever 2001).

Soil reconstruction is the most important element in creating a suitable environment for sustained plant growth in highly disturbed areas in the Arctic (Johnson 1987). Soil can usually be reconstructed by using organic material, fine grained subsoils and selecting plant species that not only grow well on existing soil, but also aid in reconstructing an optimum soil for plant growth (Johnson 1987). Reconstructing the soil not only adds nutrients to the site, but by increasing the cation exchange capacity (CEC) it helps retain nutrients added by fertilizer application. Adequate nutrients are especially important since low soil temperatures reduce decomposition rates in the soil (Johnson

1987). Using topsoil and upper soil horizons can aid plant growth by providing viable buried seed and vegetative propagules (Johnson 1987, Densmore 1992, Archibold 1984).

If a suitable soil exists on a disturbed site, seeded or naturally invading plants will inevitably become established (McKendrick 1997a). The most effective strategies to create a suitable soil and assist revegetation of disturbed tundra areas have involved physically manipulating the reclamation surface, or providing soil amendments (McKendrick 1997b). Amendments such as topsoil, inorganic fertilizer and sewage sludge can enhance nutrient availability, increase soil water holding capacity, improve the soil microbial community or ameliorate soil pH (ABR Inc. 2001).

Shallow topsoil depths in the natural environment mean insufficient topsoil will be available for reclamation of all disturbed sites. Revegetation methods tested should attempt to minimize the quantity of topsoil required while maximizing its benefits. Salvaged topsoil can be a good source of organic matter, nutrients, microbial populations and native plant propagules (ABR Inc. 2001). Inorganic fertilizer is most commonly used in reclamation to provide nutrients to soils that are deficient. However, rates of nitrogen should be reduced from those commonly used when seeding agronomic species, as higher rates could inhibit native species germination. Sewage sludge is a possible source of nutrients, and like topsoil it could provide a greater suite of micro and macro nutrients over a longer time period than inorganic fertilizer.

Provision of favorable microsites for germination can be critical. The coarse soil texture and lack of organic matter on many xeric sites cause rapid moisture loss from the surface layer. Conditions for germination are improved around larger stones which shade the soil surface and reduce evaporation (Cargill and Chapin 1987). Chambers (1995b) found that on exposed soils, relationships between soil surface characteristics and seed morphological attributes often determine the microsites of seed entrapment and retention in the zone of potential emergence, and influence patterns of seedling establishment. Several soil surface properties, including roughness, soil particle size and the amount of organic matter affect the entrapment of seeds in soils. Seed morphological attributes, including size and the presence or absence of dispersal structures can influence movement rates and distances (Chambers 1995b). Surface roughness characteristics that promote seed entrapment, such as larger particle sizes, permit seedling establishment only if small particle sizes exist in high enough percentages to provide favorable seed bed conditions. These environmental conditions include the physical and chemical properties of the soil that determine soil temperature and nutrient regimes, and ultimately have the greatest influence on seedling establishment (Chambers et al. 1990, Chambers 1995b). A properly reconstructed soil increases the number of plant species acceptable for reclamation (Johnson 1987).

2.4.2.1 Topsoil amendment

Organic amendments such as topsoil (top 10-15 cm of soil) can provide a long term benefit to the soil by increasing nutrient status, water storage capacity, biological activity and providing seed propagules (ABR Inc. 2001, Jorgenson and Joyce 1994). In recent studies (Bishop et al. 2000, Kidd and Max 2000), addition of topsoil significantly increased soil water, nutrient availability, vegetation cover and plant productivity over controls where topsoil was not added. Bishop et al. (1999) found that soil water and plant cover were significantly higher in organic topsoil treatments compared with several other amendments. Archibold (1984) found that the top 10 cm of soil in the Arctic can contain hundreds of individual seeds/m^2, suggesting that topsoil is a viable seed source. Topsoil can also increase the number of microsites due to clumps at the surface, thus increasing the probability of germination and establishment (Forbes and Jefferies 1999).

The buried seed bank is a potentially important source for native seeds (Walker 1996). Large numbers of native plant seedlings appear on recently disturbed sites before any external seeds arrive. These seedlings are concentrated on organic soils and probably come from buried seeds held in the organic layer of undisturbed tundra (Walker 1996). Applying soil organic matter after a disturbance is useful to native plant recovery because the organic layer contains the principle native plant seed source and native plant growth rates are higher in organic soils than mineral soils (Walker 1996). Higher application rates are generally more beneficial (Schuman et al. 1985, Pinchak et al. 1985), however difficult to achieve in the Arctic due to limited availability.

2.4.2.2 Sewage sludge amendment

Sewage sludge is an organic amendment which can improve properties of disturbed substrates (ABR Inc. 2001, Adriano 2001, Sort and Alcaniz 1999). It is composed primarily of organic matter, trace elements, organic chemicals, essential plant nutrients and dissolved solids and has many of the same beneficial properties as topsoil. In addition to supplying plant nutrients, the organic matter in digested sewage sludge contributes organic carbon to a rehabilitating system and can improve soil fertility and chemical and physical conditions (Adriano 2001, Rate et al. 2003, Sort and Alcaniz 1999). At the same time, because sewage is often costly to process and causes various environmental problems, its use in reclamation helps to solve the problem of its disposal (Sort and Alcaniz 1999).

Anaerobically digested sewage is not microbiologically sterile and may be a potential health hazard. Fecal coliform bacteria counts can be high (10^5 per g of dry sewage), and the spread of pathogens from the sewage into the soil and ground water system is of concern. However, research has shown the health threats posed by coliform levels are temporary as survival is quickly reduced with time especially with sewage applied in winter (Edmonds 1976, Estrada et al. 2006, Gibbs et al. 1997, Rufete et al. 2006). Gibbs et al. (1997) concluded that soil amended with biosolids could be considered free from pathogens and indicator organisms (fecal coliforms, streptococci and salmonellae) after one year following amendment. Fecal coliform survival is influenced by sunlight, temperature, moisture, organic matter, pH and the presence of competitive organisms (Rufete et al. 2006). Edmonds (1976) found fecal coliform counts decrease faster with cold temperatures, low pH, sandy soils and low soil water.

Depending on its nature, organic matter (OM) can immobilize or mobilize metals (Adriano 2001). The use of sewage sludge introduces the risk of contaminating soil/plant systems with heavy metals such as cadmium (Cd), zinc (Zn), copper (Cu), lead (Pb), selenium (Se), molybdenum (Mo), mercury (Hg), chromium (Cr), arsenic (As) and nickel (Ni). These metals can be taken up by plants following land application, resulting in increased plant tissue concentrations (Rate et al. 2003). OM can add to the sorption capacity of soils for metals rendering them less available to plants. For example, in comparing the addition of heavy metals to soil as organic salts with the addition of sewage sludge, Taddesse et al. (1991) found that Zn, Cu, Cd and Ni were less bioavailable to plants when applied in sewage sludge. The binding mechanism in sludge OM involves acidic functional groups. A large portion (50 to 80%) of OM of stabilized sewage sludge is relatively resistant to decomposition in the soil and is similar to humified OM.

If the concentrations of metals are low in the unamended soil, sewage sludge can be a useful source of trace elements to plants (Rate et al. 2003). Juste and Mench (1992) found with the addition of sludge to croplands, phytotoxicity was rarely observed in grain crops, sludge application exhibited a positive effect on plant growth in 65% of the cases, sludge borne metals remained in the zone of sludge application (0 to 15 cm) and Zn was the most bioavailable sludge borne metal, followed by Cd and Ni.

Reid and Naeth (2005) found sewage sludge to be a good amendment for improving water and nutrient holding capacities, and to increase nutrient provision and plant growth when applied at a depth of 10 cm. Bishop et al. (2001) found that sewage sludge was a significantly better amendment than inorganic fertilizer for enhancing nutrient status and plant cover over time. According to Roberts et al. (1988) sludge additions can greatly increase the total cation exchange capacity and organic carbon content of the soil, but with time and decomposition these properties decrease.

2.4.2.3 Fertilizer amendment

The climatic conditions of the Arctic severely limit the rate of nutrient input. Permafrost, by reducing the available soil depth, restricts the area of potential weathering and accumulation of nutrients. The low temperature regimes of polar regions also mean that the chemical weathering of the soil is negligible. Thus the main sources of nutrients for the plants have to be through precipitation or biological sources. The dominance of the arctic high pressure zone means that precipitation is low, therefore nutrient inputs from the atmosphere are also low resulting in low concentrations of soil nitrogen and phosphorus in arctic soils (Crawford 1989).

Nutrient concentrations of mine waste products such as processed kimberlite and glacial till are even lower than undisturbed soil and therefore are insufficient for promoting plant establishment and growth. The simplest way to increase soil nutrients and facilitate rapid establishment of cover on disturbed soils is to apply commercial fertilizers (ABR Inc. 2001, Johnson 1987). Fertilization causes an increase in total community above ground primary production and above ground biomass (Shaver and

Chapin 1986). Fertilizer rates vary with substrate and types of plant species targeted for revegetation. Helm et al. (1987) found the greatest biomass response on a disturbed wet sedge-grass site occurred when low nitrogen (N), high phosphorus (P) and low potassium (K) were applied. Greatest responses for above ground biomass and height as well as cover occurred when all three nutrients were applied (Helm et al. 1987). Fertilizer alone is not a long term solution to nutrient deficiencies (Bishop et al. 2001), because it is quickly taken up by plants, and tied up in undecomposed litter and soil organic matter (Nadelhoffer et al. 1992). According to McKendrick (1997a) phosphorus is the most limiting soil nutrient in arctic environments, followed by potassium and nitrogen and greatly benefits the establishment of grass seedlings on barren sites (McKendrick 1991). However, excessive phosphorus applications can shift species composition toward grasses and sedges and away from forbs and shrubs (Streever 2001).

Establishing dense stands of grasses grown with heavy fertilizer applications has slowed the return of natural tundra. However, when no grasses were seeded, a natural complex of tundra plants resembling the adjacent tundra utilized the fertilized area efficiently (McKendrick 1997a). Fertilizers that provide no sulfur (S), low levels of N and K and high levels of P are more beneficial for establishing native plants on mine wastes such as glacial till and processed kimberlite (Bishop et al. 2001). Processed kimberlite and glacial till are already higher in S than the predisturbed cryosol, therefore any additional S may be detrimental to plant growth.

2.4.3 Revegetation

In the Arctic, establishing a dense cover of grass (usually 60% is a common revegetation goal) within three years is not necessary, as long as soil erosion risk is low. Instead, revegetation success should rely on criteria that indicate a strong positive trend toward a functional tundra climax (McKendrick 1997a). Among the possible indicators are natural plant species seedling establishment, increasing numbers of plant species colonizing, strong vigor and reproduction (sexual and vegetative) of established plants, accumulating standing dead material in approximately three to four growing seasons, accumulating biological litter on the soil surface after three to four growing seasons and initiating a moss layer at the soil surface (McKendrick 1997a). Soil conditions, texture, hydrology, compaction, fertility, salinity and other factors affect the rate of revegetation and species of plants that will colonize and inhabit disturbed sites (Streever 2001). Recovery of arctic vegetation is a function of the nature of the disturbance (Vavrek et al. 1999). Once soil and hydrologic factors that limit plant growth are overcome, native arctic species adapted to disturbed sites will recolonize open areas. Seeding with native grass cultivars and forbs on disturbed sites can accelerate revegetation (Streever 2001).

Criteria to be considered in selecting adapted plant species for the rehabilitation of disturbed tundra are growth form, drought resistance, mineral nutrition, reproduction and growth (Brown et al. 1978). Low growing plants with extensive root systems adapt better to Arctic conditions than larger leafy species. This growth form reduces mortality caused by wind, ice abrasion and desiccation and results in abundant carbohydrate storage in the roots. High radiation loads during the growing season, strong winds and course textured soils with low water holding capacities are common in arctic disturbances, therefore plant colonization is restricted to the most drought resistant species. Vegetative reproduction capabilities are desirable because seed production is opportunistic and limited to the most favorable years. Grasses and grasslike plants which are rhizomatous are likely to provide a rapid, stable cover. Species chosen for reclamation must be capable of breaking dormancy near 0 °C, storing large quantities of carbohydrates and completing their life cycle in about 6 weeks.

Revegetation with grass seed has been the most common form of gravel pad reclamation in the Arctic (Walker 1996). Fertilizer has commonly been used to increase plant colonization rates. Species which have established on abandoned gravel pads with no revegetation efforts include *Arctagrostis latifolia* (R.Br) (Polargrass), *Artemisia alaskana* (Rydb.) (Alaska wormwood), *Artemisia borealis* (L. Pallas) (Plains wormwood), *Artemisia tilesii* (Ledeb.) (Mountain sagewort), *Astragalus alpinus* (Alpine milkvetch), *Betula glandulosa* (Michx.) (Bog birch), *Cochlearia officinalis* (L.) (Scurvy grass), *Deschampsia caespitosa* ((L.) Beauv.) (Tufted hair grass), *Epilobium latifolium* (Broad leaved willowherb), *Equisetum arvense* (L.) (Common horsetail), *Festuca rubra* (Red fescue), *Oxytropis campestris* ((L.) DC.) (Field locoweed), *Papaver lapponicum* ((Tolm.) Nordh.) (Lapland poppy), *Poa glauca* (Vahl) (Glaucous bluegrass), *Sagina intermedia* ((Lindbl.) Fries) (Snow pearlwort), *Salix ovalifolia* (Trautv) (Oval leaf willow), *Salix glauca* (Grey leaved willow), *Salix planifolia* (Nutt.) (Plane leaved willow), *Saxifraga cernua* (L.) (Nodding saxifrage), *Saxifraga oppositifolia* (L.) (Purple mountain saxifrage) and *Trisetum spicatum* ((L.) Richter) (Spike trisetum) (Walker 1996, Kershaw and Kershaw 1987). After testing many species and ecotypes within species, three grasses were identified as reliable species for seeding in the Arctic including *Poa glauca* (Glaucous bluegrass) variety Tundra, *Arctagrostis latifolia* (Polargrass) variety Alyeska and *Festuca rubra* (Red fescue) variety Arctared. These species were selected based on adaptability to the Arctic as well as potential for seed production outside the Arctic (McKendrick 1991, McKendrick 1987). Replanting with species well adapted to the soil, climate, elevation and exposure of the sites has been recommended not only for immediate revegetation, but also to establish a self perpetuating cover requiring little or no maintenance activities (Elliott et al. 1987).

2.4.3.1 Native grass cultivars

Many native grass cultivars are readily available in commercial quantities and are used for revegetation in the Arctic. Using native plants is a preferred reclamation strategy because native species are well adapted to the climate and wildlife uses of the disturbed area and require very little long term maintenance (Elliott et al. 1987, Smyth 1997). The process of identifying plant material best suited for reclamation purposes involves determining what species can be initially established on disturbed areas and, of those plants that do become established, which species survive over the long term (Elliott et al. 1987). Native grass cultivars help improve soil properties such as organic matter and nutrient contents, contribute to erosion control, and are better adapted to arctic conditions than agronomic grasses (ABR Inc. 2001).

Seeding grass initially means there is often low species diversity in the developing sward in spite of improvement in soil properties and the buildup of soil organic carbon over time (Densmore 1992). Although sites heavily seeded with grasses can develop a grass mat within a short time, particularly if fertilizers are used, dicotyledonous species can have difficulty establishing in the mat, so plant diversity remains low (Densmore 1992). Although seeded grasses create a community with low diversity, they facilitate soil development and enhance the moisture regime (Jorgenson and Joyce 1994).

Substantial amounts of organic carbon are added to the soil by the dense root network of seeded grasses. In addition, above ground plant parts increase soil moisture by capturing drifting snow, and the added organic material from decaying root mass can help increase retention of snow melt water (Jorgenson and Joyce 1994).

Certain arctic grass species frequently colonize disturbed habitats (Forbes and Jefferies 1999). For example, *Puccinellia* (Alkaligrass) species invade bare soil, but in nutrient poor soils growth is slow and plants do not reach sexual maturity for years. *Agropyron* (wheatgrass) species can germinate and establish and grow in harsh unstable conditions, and the rapid growth of vertical and horizontal rhizomes stabilizes the surface. *Poa* (bluegrass) species and *Arctagrostis latifolia* (Polargrass) are important colonizers of disturbed areas in the harsh conditions in the high arctic and form substantial mats at the surface of the soil (Kershaw and Kershaw 1987). Grass species are not well suited for very dry gravel sites, therefore, the addition of amendments is critical for revegetation success. However, native grass cultivars are extremely palatable to geese and caribou during the first three years of growth, and grazing can negatively affect stand development (Streever 2001).

2.4.3.2 Forbs

Grasses can reduce productivity of a site over time, and can inhibit colonization of other native species (Densmore 1992). Legumes appear to be well adapted to gravelly soils with low soil moisture and little organic matter (ABR Inc. 2001). Legumes naturally host bacterial symbionts capable of converting atmospheric nitrogen into a form available to plants, therefore will increase the long term availability of nitrogen in the soil. Using indigenous legumes and other forbs (*Astagalus alpinus* (Alpine milkvetch), *Hedysarum alpinum* (L.) (Alpine hedysarum), *Hedysarum mackenzii* (Northern hedysarum), *Oxytropis borealis* (DC.) (Boreal locoweed), *Oxytropis campestris* (Field locoweed), *Oxytropis deflexa* (Pall.) (Reflexed locoweed), *Oxytropis viscida* (Nutt.) (Viscid locoweed), *Aster sibiricus* (L.) (Arctic aster), *Artemisia arctica* (Less.) (Boreal sagebrush) and *Epilobium latifolium* (Broad leaved willowherb)) is critical due to the limited amount of organic topsoil and other organic amendments in the Arctic. These species have potential as early colonizers and are well adapted to dry gravelly soils

(Forbes and Jefferies 1999). Native forbs are not commercially available, therefore, their use for revegetation is limited. Several members of the *Leguminosae* (legume), *Compositae* (sunflower) and *Scrophulariaceae* (figwort) families are well suited for planting on gravel, where grasses might not persist (Streever 2001).

3.0 RESEARCH OBJECTIVES AND HYPOTHESES

The overall objective of this research was to investigate methods for establishing a self sustaining native plant cover at the Diavik Diamond Mine, NWT using available substrates, amendments and native plant species. The general hypothesis for this research was that successful soil establishment and re-establishment of a native plant community will be most assisted by appropriate soil amendments and substrates. Research objectives were to investigate soil substrates and amendments to document those most effective for enhancing soil properties and native plant community establishment and to determine the groups and individual native plant species that would establish and survive on a variety of soil substrates and amendments.

The results of this research can be used to contribute to the development of appropriate reclamation strategies for the Diavik Diamond mine, as well as other mines in the Arctic, leading to successful reclamation and minimized post closure maintenance and monitoring requirements.

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CHAPTER II. DIAMOND MINE RECLAMATION IN THE NWT: SUBSTRATES, AMENDMENTS AND NATIVE PLANT COMMUNITY DEVELOPMENT

1.0 INTRODUCTION

Diamond mining in the Canadian north has intensified since the discovery of diamonds in the Archean Slave geological province of the Northwest Territories (NWT) in 1991 (Baker et al. 2001). Diavik Diamond Mine Inc. (Diavik), currently one of the companies mining for diamonds in the NWT, is operating a diamond mine on East Island of Lac de Gras. As a pioneer in the diamond industry in Canada, Diavik has the challenge to develop successful reclamation practices to reclaim mining disturbances.

Diamond extraction is a relatively short term land use process that disrupts landscape function and integrity. Globally, diamondiferous kimberlite can be less than 1 carat (200 mg) of diamonds per tonne of ore, and diamond mining therefore typically involves the processing and disposal of large quantities of rock and tailings wastes (Baker et al. 2001). Concern over the loss of fish and wildlife habitat, degradation of pristine areas, and reduction in subsistence opportunities has prompted government agencies and private citizens to demand that areas affected by this type of disturbance be reclaimed to protect these resource functions and integrity (ABR Inc. 2001).

Successful reclamation involves re-establishment of soil processes such as nutrient cycling and native plant communities, including a diversity of shrub, grass, forb and bryophyte species. Sites requiring reclamation include gravel roads, gravel pads, waste rock and glacial till stockpiles and the processed kimberlite containment facility. Restoration, meaning the full return of a site to its predisturbance level of biological diversity and thermal, hydrologic and topographic stability (Johnson and Van Cleve 1976) is not an easily achievable goal in the north (Robus 1984). Revegetation, which is the establishment of a plant cover on a disturbed site (Jorgenson and Joyce 1994, McKendrick 1991), can be more appropriate in the short term to restore ecosystem integrity. Diavik's short term reclamation goal calls for the establishment of a stable post closure environment that protects human health and natural resources. Revegetation is a viable option to achieve this goal.

It has become increasingly important to direct tundra revegetation toward restoring the natural complex of plant species to provide productive habitat for wildlife (McKendrick 1997). Revegetation in the north faces many challenges. Plants in arctic and subarctic tundra landscapes face unique constraints on establishment and production even in undisturbed conditions (ABR Inc. 2001). Plant growth in the Arctic is primarily constrained by low air and soil temperatures, shallow depth of thaw and nutrient deficiencies (Billings 1987). Growing seasons are short (7 to 10 weeks), warm days are infrequent, and frosts can occur any day of the year. Low soil temperatures decrease organic matter decomposition rates and nutrient cycling, reduce seed production and reduce plant colonization rates of disturbed areas (Haag and Bliss 1973, Billings 1987).

Mine disturbances create obstacles for revegetating a site. The land surface associated with mining is typically waste rock or tailings wastes with few physical and chemical characteristics favorable for plant establishment and growth. The main obstacles to overcome are lack of soil moisture, soil water holding capacity and available organic matter following mining activities. Tailings can also contain high concentrations of elements such as nickel or cadmium which can be detrimental to plant growth (Clark 1995, McCabe and Otte 2000).

The Diavik project is a joint initiative by Diavik Diamond Mines, Inc. and Aber Resources Ltd. to develop a diamond mine at Lac de Gras, NWT. The project involves open pit mining, followed by underground mining, of diamond bearing kimberlite pipes. There are many buildings, roads and wastes that now disturb the landscape of the island and that will need to be decommissioned and reclaimed. Diavik has intentions of practicing progressive reclamation during the estimated 16 to 22 years that the mine will be active to prepare for eventual closure. Contouring of country rock piles to create smooth hills that allow caribou safe access and the creation of new fish habitat are examples of such reclamation (Diavik Diamond Mines Inc. 1999). East Island is to be reclaimed to wildlife habitat upon mine closure. Habitat is the place where an animal lives, which includes all the resources necessary for survival (Diavik Diamond Mines Inc. 1999), therefore revegetation using native species is critical for reclamation.

Little research has been done on diamond mine reclamation using native species in the Arctic. Due to the physical and chemical properties of the diamond mine waste materials, low soil water, nutrients and organic matter, limited dispersal of native propagules and no groundwater input, gravel pads can remain barren for years following a disturbance (Walker 1996, Streever 2001). Techniques used for improving soil structure and nutrient availability including organic topsoil, inorganic fertilizer, peat moss, fine grained substrates and sewage sludge have been researched in combination with various native plant species with varied results (Jorgenson and Joyce 1994, ABR Inc. 2001, Reid and Naeth 2005a, Stevens 2006). Bishop et al. (2001) found topsoil significantly increased vegetation cover and plant productivity when used as an amendment in the north. Reid and Naeth (2005a) found sewage sludge to be an appropriate amendment to enhance vegetation success on processed kimberlite tailings waste. Stevens (2006) found peat and processed kimberlite combined make a suitable plant substrate. Inorganic fertilizer has been found to not be a viable long term management strategy, although it facilitates rapid establishment of plant cover on disturbed soils (Bishop et al. 2001, Reid and Naeth 2005a and 2005b). However, there has been little research on the suitability of glacial till as a substrate for plant growth, alone, or in combination with other waste materials and amendments.

Evaluation of plant materials for revegetation of disturbed arctic landscapes has been ongoing since the early 1970s (Johnson and Van Cleve 1976). Early revegetation efforts in the arctic introduced non native grasses and legumes, however, this method proved unsatisfactory because these species were poorly adapted to arctic conditions, required repeated fertilization and impeded the establishment of natural colonizers (McKendrick 1997, Forbs and Jefferies 1999). With the exception of a few native grasses, few native northern species are available in commercial quantities, therefore, revegetation efforts directed toward determining suitable native species for reclamation at diamond mines are critical for successful reclamation in the future.

2.0 OBJECTIVES

The objective of this research was to determine which combination of substrate, amendment and native plant species would be most beneficial for reclamation of the Diavik Diamond Mine. The challenges are to recreate an environment that resembles the existing adjacent undisturbed tundra using only locally available materials and native species and to limit the use of fertilizer and other maintenance activities to create a self sustaining ecosystem. Specific short term objectives were as follows.

- Determine which substrates were most effective for enhancing soil properties and native plant community development.
- Determine which soil amendments were most effective at enhancing substrate properties (texture, organic matter, nutrients and water holding capacity), native plant establishment and community development.
- Determine which groups and individual native plant species would establish and survive on a variety of soil substrates and amendments.

3.0 MATERIALS AND METHODS

3.1 Site Description

Diavik Diamond Mine Inc. is located on a 20 km^2 island, called East Island, on Lac de Gras approximately 320 km northeast of Yellowknife NWT (64° 31' North, 110° 20' West) (Figure 2.1) (Diavik 2002). The total area affected by the mine will be approximately 22 km^2. Lac de Gras is located in the sub-arctic tundra on the Precambrian shield and is in an area of continuous permafrost. The area is characterized by short summers with cool temperatures and long, cold winters. Weather at Diavik is greatly modified by Lac de Gras compared to inland locations.

The area consists mainly of massive Archean rocks that form rock outcrops and glacial deposits of boulders, till and eskers. The landscape of East Island is characterized by steep sided bedrock outcrops, undulating to strongly rolling morainal deposits, ridged and hummocky glacio-fluvial deposits and level to depressional glacio-lacustrine and organic deposits (Diavik Diamond Mines Inc. 1999). Soils in the area are typically classified as turbic and static cryosols.

The northern limit of the Southern Arctic Ecozone where Diavik is located provides a transition between taiga forest and arctic tundra vegetation. Vegetation in upland areas is dominated by dwarf shrubs, and is generally sparse and stunted. Sedges and mosses dominate in low lying wet tundra. Due to the exceedingly dry climate, short growing season, frost churned and calcareous soils and high winter wind speeds, plant colonization is only possible for the hardiest of species. Dominant species in heath tundra communities on the island include *Betula glandulosa* (Michx) (Bog birch), *Salix glauca* (L.) (Grey leaved willow), *Salix planifolia* (Pursh) (Plane leaved willow), *Vaccinium vitis-idaea* (L.) (Bog cranberry), *Vaccinium uliginosum* (L.) (Bog bilberry) and *Empetrum nigrum* (L.) (Crowberry). *Eriophorum angustifolium* (Honck.) (Narrow leaved cotton grass), *Eriophorum vaginatum* (L.) (Sheathed cotton grass), *Carex aquatilis* (Water sedge) and *Calamagrostis inexpansa* (A. Gray) (Northern reed grass) dominate wet tundra communities. Both communities surround the research site.

The research site was established in 2004 on a raised gravel pad, previously used for ammonium nitrate storage (Figure 2.2). The raised pad was constructed of a layer of boulders over tundra, followed by a layer of small to mid sized rocks, topped with a 50 cm layer of gravel. The majority of disturbed areas requiring reclamation following mine closure are raised gravel beds similar to the research site. Ammonium nitrate bags were stored on impermeable tarps, which have been removed, so contamination was not an issue. The site was mostly gravel which has low water holding capacity, nutrients and organic matter (Forbes and Jefferies 1999). To enhance some of these properties and enhance plant growth, substrates and amendments were added.

3.2 Experimental Treatments

Five substrates, five soil amendments, six seed mixes and two seasons of seeding were studied based on availability, previous reclamation research at diamond mines in northern regions (ABR Inc. 2001, Reid and Naeth 2005a and 2005b) and Diavik's Reclamation Research Plan (2002). The substrates included glacial till (Till), fine processed kimberlite (PK), PK and Till in a 50/50 mixture (50/50), PK and Till in a 25/75 mixture (25/75) and no substrate (Gravel). The amendments included topsoil (Topsoil), sewage sludge (Sewage), inorganic fertilizer (Fertilizer), sludge from the north inlet water treatment facility (Sludge) and no amendment (None). The seed mixes included grasses (Grasses), forbs (Forbs,) grasses without aggressive species (G-A), esker species (Esker), adaptable species (Adaptable) and no seeding (No Seed) (Tables 2.1 and 2.2). Four additional seed mixes were only included in 2 replications (blocks 1 and 3) due to space limitations and included wet tundra species (Wet Tundra), heath species (Heath), wild collected seed and birch (Birch).

3.2.1 Substrates

Glacial till is the most readily available waste material at the mine site, however, little research has been conducted on its potential use in revegetation of disturbed areas. The material is overburden material from the pit and ranges from clay size particles to boulders 1 m in diameter. This range in particle size can be beneficial for revegetation because the number of microsites is increased. Microsites are defined as the environment immediately surrounding a seed which is favorable for germination and establishment (Forbes and Jefferies 1999).

Few published studies are available on the environmental management of kimberlite materials (Baker et al. 2001). Leakage of alkaline drainage with elevated total dissolved solids, sulfate and chloride from kimberlite tailings facilities has been documented in Siberia (Borisov et al. 1995). Diavik kimberlite materials are predominantly composed of silicon, magnesium and iron, and the most abundant trace elements are nickel, chromium, cobalt, strontium and zinc (Baker et al. 2001). Baker et al. (2001) showed that processed Diavik kimberlite has a high total sulfur content and neutralization (acid consuming) potential and all material disposed as processed kimberlite is expected to generate alkaline drainage (pH = 8.0 to 8.5) containing elevated total dissolved solids and low but detectable concentrations of metals such as aluminum, nickel, cobalt, strontium and zinc. Processed kimberlite has poor physical and chemical properties for supporting plant growth, including low nutrients, no organic component, poor water holding capacity and very low calcium. However, it has been investigated at the BHP Diamonds mine site, and found adequate as a substrate to establish plants if amended (Reid and Naeth 2005a).

Initial soil analyses indicated that PK is composed of greater than 95% sand, while till has less sand (68%) and greater silt (27%). Combining glacial till and PK could increase water holding capacity and nutrient holding capacity which is beneficial for plant growth. Different combinations of the two substrates would likely affect soil properties differently, thus influencing plant establishment and development differently. PK is not as readily available for reclamation as glacial till, therefore it would be beneficial if less could be used without negatively influencing plant establishment and growth.

Substrates stockpiled at Diavik were brought to the research site with 100 ton heavy hauler trucks and dumped in piles in September 2004. The substrates were then spread onto the gravel plots to a depth of 30 to 40 cm with a 966 Cat loader. When the substrate was a mix, the appropriate quantities were determined by placing one bucket of processed kimberlite for every bucket of glacial till for the 50/50 mix, and one bucket of processed kimberlite for every three buckets of glacial till for the 25/75 mix in a pile in the middle of the plot. The substrates were then leveled with the 966 Cat loader by dragging the bucket over the substrate.

The no substrate (Gravel) plots serve as a control for this research. These plots received the same amendment and seed mixes as the other plots, therefore differences between plots can be attributed to the substrates.

3.2.2 Amendments

Salvaged topsoil can be a good source of organic matter, nutrients, soil microorganisms and native plant propagules. Shallow topsoil depths and difficult stripping conditions in the natural environment mean insufficient topsoil will be available for reclamation of all disturbed sites. Revegetation methods will need to minimize the quantity required while maximizing its benefits. Topsoil at the mine was stripped from a wet tundra environment and likely included the O, A and B horizons. Stripping of heath environments would be more beneficial for revegetation due to the presence of species adapted to drier conditions, however is very difficult due to boulders, exposed rock and rock outcrops.

Sewage sludge, a waste product at the mine site, could be a source of nutrients and provide a greater suite of micro and macro nutrients over a longer time period than inorganic fertilizer. Use of on site waste products would reduce operational expenses required for their disposal. Sufficient solid sewage for all treatments was not obtained in fall 2004, therefore this amendment was only added to the 50/50 fall treatments. Sufficient material was not available in spring 2005 to be applied to all substrates therefore was only applied to the 50/50 spring treatments and the spring Till treatments. It was hypothesized that the 50/50 and Till substrate materials would benefit the most from sewage amendment and would be the most readily used materials at the mine site. The sewage material in 2004 was more decomposed and heterogeneous than the 2005 sewage.

The topsoil and sewage sludge amendments were hauled to the study site with dump trucks and spread onto the plots with a 966 Cat loader in September 2004. Spreading and leveling the amendments with a bobcat backhoe resulted in the amendments being incorporated into the substrates up to a depth of approximately 5 cm. Topsoil was applied with a bobcat backhoe to a depth of 10 cm, at a rate of approximately 12 tonnes/strip or a total of 180 tonnes for the entire site (Appendix B). This rate was based on material availability. Sewage sludge was applied with a bobcat backhoe to a depth of 10 cm at a rate of 12 tonnes/strip, or 180 tonnes in total. Reid and Naeth (2005b) found sewage sludge significantly improved plant growth when applied at this rate. The sewage was in a semi solid state when applied which reduced runoff during application.

Inorganic fertilizer is most commonly used in reclamation to provide nutrients to soils that are deficient and a standard reclamation formulation is usually applied. However, in the Arctic, nitrogen (N) application rates should be reduced from those commonly used when seeding agronomic species as higher rates may inhibit native species germination (Forbs and Jefferies 1999). Preliminary soil analyses showed that the soils were already high in potassium (K) and sulfur (S) and low in phosphorus (P), therefore, a commercially available, granular 11-52-0 fertilizer was applied to both spring and fall seeded plots between August 9 and 16, 2005 and on July 23, 2006. In August 2005, the only fall seeded plots that had been seeded were the Grasses and Forbs, therefore, only these two plots received fertilizer in 2005. This fertilizer provided low levels of N and K and high levels of P, which is recommended from research for establishing native vegetation at mine sites in the arctic (ABR Inc. 2001). The fertilizer was broadcast by hand at rates dependent on subplots. The rates were based on P, which is the most limiting nutrient and differed for each substrate (Table 2.3 and Appendix B).

Sludge from the North Inlet Water Treatment Plant (NIWTP) was tested in 2005 as an amendment to enhance substrate properties and plant growth. Sludge produced by the NIWTP consists of particulate matter from ground rock, old lake bed sediment, till that has collected at the bottom of the open pit and wastewater from seepage and runoff (de Rosemond and Liber 2005). The sludge is slightly higher than the Canadian Council of Ministers of the Environment (CCME) (2003) agriculture guidelines in arsenic, barium (380.91-920.72 mg/kg), chromium (40.73-122.66 mg/kg), copper (69.39-119.36 mg/kg) and nickel (130.80-253.57 mg/kg), however, the concentrations are of little toxicological concern because they will be diluted when applied over the land surface. It was low in total organic carbon, but high in ammonium which can be beneficial to plants. The sludge was approximately 81% sand and 12% silt with very high water content (~92%), and therefore, it had poor consistency for land application. The sludge was applied by hand to a depth of 3 to 4 cm to the 25/75 and PK treatments between June 28 and July 5, 2005 (Figure 2.5 and Appendix B).

3.2.3 Seed mixes

A suite of grass and forb species native to the sub-arctic tundra were the main plant species used. Commercially available native species are mainly limited to grasses and a few legumes. Seed was purchased through Arctic Alpine Seed Ltd. out of Whitehorse. Six main seed mixes were sown in all three blocks (Table 2.1), four additional mixes were only seeded in blocks 1 and 3 due to space limitations. Seed was wild collected on East Island during summer 2005 dried and squashed prior to seeding. Not enough seed was available for both spring and fall seeding therefore separate plots in blocks 1 and 3 were seeded in early September 2005 with wild collected seed of *Empetrum nigrum* (L.) (Crowberry), *Arctostaphylos rubra* ((Rehd. & Wilson) Fern.) (Bearberry), *Ledum decumbens* ((Ait.) Hultén) (Dwarf labrador tea), *Loiseleuria procumbens* ((L.) Desv.) (Alpine azalea) and *Betula glandulosa* (Michx.) (Birch).

Eleven native grass cultivars were used (Tables 2.1 and 2.2) based on previous arctic research and characteristics which would provide benefits in revegetating the disturbed site (Appendix A). The mixes were seeded at a rate to obtain 50 plants/m^2, therefore each species in the Grass mix was seeded at 4.5 plants/m^2 (based on weight) (Appendix B). Each species was seeded at an equal rate to determine effectiveness of the treatment by keeping as many variables constant as possible. The grasses without the aggressives (G-A) species mix was seeded at a rate of 7 plants/m^2 to obtain the desired 50 plants/m^2, as there were only 8 species in the mix. The aggressive species (*Festuca rubra* (L.) (Red fescue), *Calamagrostis canadensis* (Michx.) (Bluejoint) and *Agropyron pauciflorum* ((Schwein) Hitchc.) (Slender wheatgrass) were removed to eliminate heavy competition between species, and to determine if aggressive species hinder natural encroachment. In the Esker mix, the four grass species and *Epilobium latifolium* were seeded at a higher rate of 10 plants/m^2, because there were only 6 species in the mix, and the *Oxytropis campestris* was seeded based on availability (8 plants/m^2). The Adaptable mix consisted of five grasses seeded at a rate of 8 plants/m^2 to achieve the desired plant cover and one forb species in the mix was seeded based on availability (67 seeds/plot). Insufficient seed was wild collected to achieve this rate, therefore seed was equally divided among plots. Species were seeded at these rates to allow enough space and nutrients for natural encroachment and still provide sufficient cover for erosion control.

Five native legume or forb species (Tables 2.1 and 2.2) were chosen based on previous research in the Arctic and individual properties appropriate for the site conditions (Appendix A). Forb seeding rate was based on available seed; *Hedysarum mackenzii* (Rich.) (Northern hedysarum) 67 seeds/plot, *Hedysarum alpinum* (L.) (Alpine hedysarum) 67 seeds/plot, *Oxytropis splendens* (Dougl. ex Hook) (Showy locoweed) 28 seeds/plot, *Oxytropis deflexa* (Pall.) (Reflexed locoweed) 64 seeds/plot, *Epilobium latifolium* (L.) (Broad leaved willowherb) 67 seeds/plot and *Oxytropis campestris* (L.) (Northern yellow locoweed) 56 seeds/plot.

3.2.4 Season of seeding and methods

Seed mixes were sown in spring and fall to determine if season of seeding has an effect on establishment and growth. All grass and forb species were weighed to ensure appropriate rates were applied to each plot. Seeds were broadcast by hand and incorporated into the soil with a rake where possible. Some of the amendments, such as topsoil, could not be raked thoroughly. The Grasses and Forbs seed mixes were broadcast seeded in mid September 2004, so seed could use the early spring moisture in 2005. Although seeding all ten mixes was planned, extremely windy weather prevented this. The remaining fall treatments were seeded between August 30 and September 2, 2005.

All seed mixes were sown in spring treatments between June 21 and July 5, 2005. Methods were the same for fall and spring seeding.

3.3 Experimental Design

Research plot construction started between July 27 and August 3 and was completed between September 14 and 21, 2004 for fall seeding treatments. A 16 G grader with 25 cm ripping tines on the back scarified the site to a depth of approximately 20 cm in July 2004.

An incomplete randomized design was used in this study. Five substrate treatments, five amendment treatments, two seasons of seeding treatments and six seed mix treatments were applied to each of three replicates (blocks). Five substrate plots of equal area were established within each of the three blocks (Figure 2.3). Substrate plots in blocks 1 and 3 were approximately 300 m^2 and 150 m^2 in block 2. Each plot was randomly assigned one of five substrate treatments. A 30 to 40 cm cover was applied with a front end loader; when the cover was composed of two materials they were combined to achieve the 30 to 40 cm depth. Each of these five substrate plots was then divided into four amendment strips of equal size. Each strip was oriented north to south and divided in half for season of seeding treatments. One of four soil amendment treatments was randomly assigned to each strip. Due to lack of materials, one of the amendments (sewage) was only applied to two of the substrate treatments (50/50 and Till) and therefore another amendment was introduced into the study (sludge) and applied to two of the remaining substrates (25/75 and PK). The amendment strips were then divided into 6 to 10 subplots (approximately 5 m^2), and one of six seed mixes (Tables 2.1 and 2.2) was randomly assigned to each for seeding either in spring or fall (Figure 2.4).

Throughout the remainder of the thesis, treatments will be written as substrate first and amendment second, for example, 50/50 Topsoil. When there was no amendment added, only the substrate will be listed, for example, 50/50 (Appendix B). Samples from undisturbed tundra were taken using the same methods as at the research site to make comparisons between the soil being created with substrates and amendment and undisturbed topsoil (reference soil).

Inclusion of all combinations of substrates and amendments allows for conclusions to be made on the effectiveness of each, alone and in combination. Given the dominance of herbaceous vegetation and small shrubs in this arctic environment, the subplots provide sufficient area to assess species performance including their ability to propagate. Large scale trials can be conducted once the number of treatments is reduced through this initial study.

3.4 Monitoring And Evaluation

3.4.1 Meteorological parameters

Meteorological data have been collected on East Island of Lac de Gras since 1999 by Diavik Environment Department. The meteorological station located west of the mine site measures wind speed, wind direction, precipitation, ambient air temperature, incoming solar radiation and relative humidity, hourly. Due to equipment failure wind speed and direction is only available for 2005 and 2006.

3.4.2 Soils

Three randomly located soil samples were collected from each treatment plot in September 2004. Plots that were to be established and seeded in spring 2005 were sampled in spring 2005. At each location, samples were taken from 0 to 10 cm and 20 to 30 cm with a 4 cm dutch auger and placed in plastic bags. Samples were kept cool in a refrigerator until delivered to Enviro-Test Laboratories in Edmonton for analyses.

Soil samples sieved to remove large gravel particles, ground to <2 mm and the following analyses were conducted. Available P and K were determined using a modification of the Kelowna extraction method (Qian et al. 1994). Available N and S were determined by a calcium chloride extraction method (Carter 1993). Water soluble cations (calcium, potassium, magnesium and sodium) and pH were measured using a saturated soil paste method (McKeague 1978). Cation exchange capacity (CEC) and exchangeable cations were determined by the barium chloride extraction method (McKeague 1978). Total carbon was determined using a Leco Furnace combustion method (Carter 1993). Total organic carbon was determined by the Walkley Black method and total inorganic carbon was calculated from the difference between total carbon and total organic carbon. A third of the samples were analyzed for metals restricted in concentration by the Canadian Council of Ministers of the Environment including silver, arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, mercury, molybdenum, nickel, lead, antimony, selenium, tin, thallium, uranium, vanadium and zinc using the ICP atomic emission spectroscopy technique (EPA 1994). Samples taken in the sewage sludge plots were analyzed for fecal coliform using the membrane filtration technique, and *Salmonella* using the multiplex polymerase chain reaction assay (Way et al. 1993).

Soil physical parameters, particle size, soil water content and soil temperature were measured to establish a basic understanding of plant growing conditions compared to undisturbed cryosols. Only one third of the samples were analyzed for particle size due to budget constraints. Particle size analysis was performed using the hydrometer method (Gee and Bauder 1986). Manufacturer calibrated soil water and temperature Smart Sensors^{TM} were installed in each treatment ($n = 3$) just above the gravel pad substrate interface (at a depth of approximately 30 to 35 cm) and 10 cm below the surface. Data were collected on an hourly basis for the two years of the study using onset HOBO Micro Stations (Onset Computer Corp). Stations were mounted above ground level to prevent flooding or snow burial. Not all of the HOBO Micro Stations recorded data for the entire winter due to low temperatures and battery failure, however, they were reset in the spring to record during the growing season.

3.4.3 Vegetation

Vegetation parameters were measured between August 9 and 16, 2005 and July 17 and 24, 2006. This was the most appropriate time for measurement because it was late enough in the growing season to ensure winter annuals were established and early enough to include annuals, biennials and perennials before they senesced. Due to the remote location of the study site and the high cost of transportation to access the site, vegetation parameters were only measured once a year for two years. An initial assessment of density was conducted in 2005, however, due to poor emergence it was very difficult to identify grass species. Vegetation parameters measured for each species in 2006 included density by species and plant health and height. Ground cover could not be assessed at this time due to relatively low emergence rates.

A buffer around each small plot was not sampled to remove the edge effect from neighboring treatments. Each 5 m^2 subplot was sampled using a 20 x 50 cm quadrat in three random locations. Based on species area curves, three samples provided sufficient information regarding density and richness of each species in the subplot.

Mean height was estimated based on all individuals rooted within the quadrat by stretching the plant out and measuring the tallest and shortest standing individuals, then averaging the height. Overall plant health for individuals within each quadrat was based on a 4 point scale. Individual plants greater than 50% dead were assigned a health value of 1; individual plants 25 to 50% dead were assigned a 2; individual plants 5 to 25% dead were assigned a 3; and green, robust, healthy individual plants less than 5% dead were assigned a health value of 4. Within each quadrat, species density was determined by counting and identifying individual species rooted within the quadrat.

3.5 Statistical Analyses

Substrates and amendments were not sampled separately, thus could not be considered independent from each other. They were combined and called treatments and analyzed together. An average among repetitions (blocks) one, two and three for each treatment was determined and statistics were performed on the means. Normality was assessed through visual inspections of the data on histograms and probability plots and by calculating a g_1 value for skewness, and a g_2 value for kurtosis (Zar 1999). Shapiro-Wilk's test for normality and Levene's test for equal variances were conducted prior to analyses. Most variables were normal (75 to 80%), however, due to the small sample size only some of the variables met homogeneity of variance. The analysis of variance and the *t*-test are robust with respect to the assumption of the underlying population's normality, and the validity of the analyses are affected only slightly by even considerable deviations from normality (in skewness and/or kurtosis) (Zar 1999). Since most of the data were normal, according to the central limit theorem, the distribution of means form a non-homogeneous population that will tend toward normality as sample size increases (Zar 1999). Given the small sample size, tests of the homogeneity of variance are skeptical and presentation of both transformed and untransformed data and parametric and non-parametric statistical analyses would have complicated interpretation (Finney 1989), thus untransformed data and parametric analyses were used for all statistical analyses.

A Type III one way analysis of variance was performed with SPSS statistical software on all treatments (i.e., each combination of substrate and amendment) to determine significant differences among treatments for all soil and vegetation parameters measured (Zar 1999). Significant treatment effects were further analyzed using Tukey's post hoc test. In all statistical analyses, a confidence level of 95% was chosen ($\alpha = 0.05$) to distinguish statistically significant variation.

A two sample *t*-test was conducted to determine significant differences between means of spring and fall seeded plots. The null hypothesis states that there is no difference between spring and fall seeded plots on each treatment and was rejected if the calculated statistic was greater than the critical value with $\nu_1 + \nu_2 - 2$ degrees of freedom ($t_{\alpha(2),\ \nu1+\nu2-2}$) (Zar 1999).

4.0 RESULTS AND DISCUSSION

4.1 Meteorological Parameters

Mean annual temperature at the mine site for the last seven years was -9.1 °C (Table 2.3) and mean annual precipitation was 315 mm (Diavik data). Less than half of this precipitation comes as rain during the growing season. The growing season begins mid May when air temperatures remain above 0 °C and ends mid September when air temperatures frequently drop below 0 °C. Mean monthly air temperature during the growing season (June, July and August) for the study years was 10 °C and mean monthly precipitation was 26 mm. Temperatures during the growing season ranged between 1 and 20 °C, which may negatively influence plants. For example, a temperature fluctuating between 10 and 20 °C and averaging 15 °C does not have the same effect on plants as a constant temperature of 15 °C. Growth in plants which are normally subjected to variable temperatures tends to be depressed, inhibited or slowed compared to growth in plants subjected to constant temperature (Odum 1953).

The prevailing wind direction at the mine site is from the north-northeast and average wind speed is generally between 0 to 5 m/s. Wind speeds in 2005 and 2006 between 5 and 20 m/s occur over 30% of the time (Diavik data).

4.2 Soils

4.2.1 Soil texture

Soil texture at both 0 to10 cm and 20 to 30 cm depth increments for all treatments was generally loamy sand to sandy loam with the exception of a few sand textured treatments. Gravel treatments had a sand texture with sand and clay at 86.7 and 2.5%, respectively, while undisturbed topsoil (reference soil) on East Island of Lac de Gras had a sandy loam texture with sand and clay at 64 and 5.5%, respectively (Tables 2.4 and 2.5). All treatments with the exception of Gravel Fertilizer increased clay. Treatments that most closely approached the texture of undisturbed topsoil included Till Topsoil, Till None, Till Fertilizer, Till Sewage and PK Topsoil. Treatments farthest from a sandy loam texture included Gravel None, PK, PK Fertilizer and PK Sludge. All other treatments were closer in texture to undisturbed topsoil than to the Gravel treatment.

4.2.2 Soil temperature and soil water

Mean, maximum and minimum soil temperature and water content were determined by treatment for 2004/2005 and 2005/2006 winter seasons, and 2005 and 2006 growing seasons (June, July and August) (Tables 2.6, 2.7, 2.8, 2.9 and Appendix B). For 0 to 10 cm, soil temperature increased earlier in spring, was generally higher, went through more extreme ranges and decreased earlier in fall than at 20 to 30 cm. Treatments with PK and Gravel got substantially colder during winter and the Gravel treatment was generally below the mean during the growing season. Soil temperature depends upon mineral composition, organic matter and the volume of fractions of water and air. The coarse sand texture in PK and Gravel treatments created a lower porosity with less inter aggregate pores to trap warm air. Water in these soils was lower, resulting in surface pores being filled with air rather than water. Since air is a poor heat conductor, soil temperature remains lower. Surface temperature in PK treatments was generally higher than the mean during the growing season due to the dark color of the material absorbing more latent heat than lighter colored treatments.

During the growing season, soil water was lowest in June and highest in August. Mean soil water among treatments did not differ substantially with the exception of Gravel treatments having lowest soil water and Sewage treatments having highest soil water. The difference in water content between these treatments was likely largely due to texture and organic matter. Clay in a soil has a dominant influence on many physical and chemical processes because of its very large surface area. Soils with higher clay have higher water holding capacities due to higher porosity created by smaller particles. Organic matter binds soil particles together promoting aggregation, and in turn increases porosity and surface area of a soil. The Sewage treatment had a loamy sand texture, and higher clay and organic matter resulting in higher porosity and surface area, and thus more surfaces for water to adhere to. The Gravel treatment had a sandy texture resulting in larger pores compared to the other treatments which facilitated internal drainage.

Water content for these soils appears to be low, however, without data from nearby undisturbed soil it is difficult to determine if values are representative. Soil water would likely be lower in this tundra environment than in a temperate environment because total growing season precipitation is more than twice as high in a temperate environment than it is at the mine site.

4.2.3 Soil nutrients

All elements essential for plant growth, except carbon and oxygen, are obtained from soil by terrestrial plants. Relatively few inorganic elements are required by plants, however macro nutrients, N, P, K, S, calcium (Ca) and magnesium (Mg) are required in large amounts, and micro nutrients, iron (Fe), manganese (Mn), boron (Bo), copper (Cu), zinc (Zn), molybdenum (Mo), sodium (Na), chlorine (Cl), cobalt (Co), vanadium (V) and a few more are required in trace amounts (Adriano 2001). Excessive amounts or lack of any of these elements can cause poor plant growth and toxicity or deficiency problems.

Nitrogen is often a limiting nutrient in tundra communities due to low decomposition and mineralization rates (Schimel et al. 1996). Available N (NO_3^- and/or NH_4^+) varied among treatments, but differences were not statistically significant. Available N was highest in Sewage (34 mg/kg) and lowest in Topsoil treatments (3.1

mg/kg) (Table 2.10). All treatments were higher in available N than undisturbed topsoil (1.8 mg/kg), therefore plants will likely not be nitrogen deficient.

The only widespread source of phosphorus in the Arctic is from precipitation, which is very limited, therefore soil phosphorus (P) is extremely low (Crawford 1989). Although there was no significant difference between Fertilizer treatments and Topsoil and no amendment treatments, the amount of available P (either $H_2PO_4^-$ or HPO_4^{2-}) increased from approximately 4 mg/kg with no amendments to 18 mg/kg in Fertilizer treatments (Table 2.10). Although native arctic plants are adapted to low soil phosphorus, they grow better when phosphorus is readily available (Crawford 1989). Available P in Sewage treatments was significantly higher than all other treatments at both 0 to 10 and 20 to 30 cm depth increments.

Potassium (K) is absorbed in larger amounts than any other nutrient except nitrogen in plants and is naturally high in arctic soils. Its origin in soils is from the many potassium rich minerals such as orthoclase, biotite and muscovite. Although all treatments were high in K (41.6 to 330.3 mg/kg), PK treatments (with the exception of PK Topsoil) were elevated above undisturbed topsoil (117.2 mg/kg), and consequently 50/50 and 25/75 treatments were also elevated (Table 2.10). PK had higher K because of the 2:1 type structure of the phyllosilicate mineral muscovite of which it is composed. Potassium is the dominant interlayer structural cation held in position to bind the successive 2:1 layers together and satisfies the negative charge. It is released when the mineral breaks down, and thus K increases in PK. Sewage treatments were also higher in K than all other treatments. The increased CEC due to higher clay and organic matter in Sewage treatments resulted in more K being attenuated in the soil and thus increased concentrations of available K.

Available S ranged from 9.8 mg/kg in undisturbed topsoil to 133 mg/kg in Till Sewage treatments and was significantly lower in the Gravel, Gravel Fertilizer and 25/75 Topsoil treatments (Table 2.11) than Till Sewage, PK, PK Fertilizer and 25/75 Sludge treatments at the 0 to 10 cm depth increment. There were no statistically significant differences among all other treatments including undisturbed topsoil at the 0 to10 cm depth increment. At 20 to 30 cm, PK treatments were significantly higher than Gravel treatments, and consequently 50/50 and 25/75 treatments were also higher (Table 2.11).

Although all treatments were significantly higher in Ca than undisturbed topsoil (9.4 mg/L), there were no statistically significant differences among treatments at 0 to 10 cm (Table 2.12). Results were similar for 20 to 30 cm with the exception of the 25/75 Fertilizer treatment, being significantly higher than Gravel, Gravel Fertilizer and Gravel Topsoil treatments (Table 2.13). Mg varied extensively among treatments, being highest in PK treatments (346.1 mg/L) and lowest in Gravel Topsoil (28.3 mg/L), Till Topsoil (25.8 mg/L) and undisturbed topsoil (6.0 mg/L) treatments at 0 to 10 cm (Table 2.12).

Na is not an element that plants normally need nor is it toxic at low concentrations (Bradshaw and Chadwick 1980). However, at elevated concentrations it can reduce plant growth, or cause growth to cease. Na at the 0 to 10 cm depth increment ranged from 6.8 mg/L in undisturbed topsoil to 149.9 mg/L in Till Sewage treatments (Table 2.12). Na concentrations in Sewage, Sludge and PK treatments were significantly higher than in Topsoil and no amendment treatments.

4.2.4 Fecal coliforms and salmonella

Salmonella was isolated in one sample from Block 2, 50/50 Sewage, in fall 2004. It was not isolated from any 2005 samples (spring 50/50 Sewage and Till Sewage treatments). Fecal coliforms were found in all sewage amended treatments. Fecal coliform numbers were lowest in the Block 2 Till Sewage treatment (either below or slightly above the detection limit of 3 MPN/g) (Appendix B). This sewage was brought to the site in fall 2004, and applied in spring 2005. While being applied to the treatment, it was mixed with gravel and thus was unintentionally diluted. Sewage in Block 1 and Block 2 50/50 treatments had fecal coliforms of 500 MPN/g. Block 1 Till sewage had approximately 900 MPN/g and Block 3 Till at approximately 1000 MPN/g. Research on surface applied sewage has shown coliform survival rates decrease with time, especially with decreasing temperatures (Edmonds 1976, Estrada et al. 2006, Rufete et al. 2006). Fecal coliform bacteria decreased in sewage stockpiled over winter at the research site and were higher in sewage brought to the site and subsequently applied.

4.2.5 Soil chemistry

Cation exchange capacity ranged from 2.3 meq/100 g in Gravel treatments to 18.5 meq/100 g in undisturbed topsoil at the 0 to 10 cm depth increment (Table 2.14). In general, at both depths, PK treatments were significantly higher than Till treatments with the exception of PK Topsoil (Tables 2.14 and 2.15). CEC of PK and PK Fertilizer treatments were inconsistent with particle size. For example, the PK treatment had a CEC of 11.8 meq/100 g and 3.7% clay. Since CEC is attributed to clay in the soil, the CEC for 100 grams of the clay fraction would be approximately 320 meq/100 g. There are no known phyllosilicates with CEC that high. Due to increased clay and organic matter, Topsoil and Sewage treatments increased CEC for all substrates, however the increase was not statistically significant.

Soil pH ranged from 4.5 in undisturbed topsoil to 8.2 in PK at the 0 to 10 cm depth increment (Table 2.14). For each substrate Topsoil treatments had the lowest pH and treatments with no amendment had the highest. At 20 to 30 cm there were no statistically significant differences among treatments, with the exception of undisturbed topsoil being significantly lower than all other treatments except Till, Till Topsoil, Till Fertilizer and PK Topsoil. Although there were statistically significant differences among treatments, all were within an acceptable pH range for plants. Soils in the Arctic are generally slightly acidic (Smyth 1997, Marion et al. 1997, Schmiel et al. 1996) and disturbance increases pH. However, Chapin and Shaver (1981) found plants adapted to the Arctic are capable of surviving within a pH range of slightly acidic to slightly alkaline.

Although little research has been conducted in the Arctic on effects of increased electrical conductivity (EC) and sodium adsorption ratio (SAR) on native plant species, an EC of <2 dS/m and an SAR of <4 will generally not negatively affect plant growth. EC ranged from 0.2 dS/m in undisturbed topsoil to 7.1 dS/m in the Till Sewage treatment at 0 to 10 cm. The addition of sewage and sludge increased EC to >2 dS/m, however all other treatments (with the exception PK and PK Fertilizer treatments being 3.0 dS/m and 2.7 dS/m, respectively) were <2 dS/m at 0 to 10 cm. At 20 to 30 cm, not only are Sewage and Sludge treatments >2 dS/m, increased EC in PK resulted in PK, 50/50 and 25/75 treatments also being >2 dS/m (Table 2.15). Increased EC at the 20-30 cm depth in the PK Sewage and PK Sludge treatments could have been due to leaching of the amendments. SAR was <4 in all treatments, at both depth increments, therefore increased sodium concentrations should not negatively influence plant establishment and growth (Tables 2.14 and 2.15).

Addition of sewage and topsoil amendments significantly increased total carbon (TC) and total organic carbon (TOC) for all substrates at the 0 to 10 cm depth increment (Figure 2.6 and Table 2.14). Organic carbon increases available nutrients in a rehabilitating system by increasing CEC and can improve soil physical (texture, water holding capacity and bulk density) and chemical (CEC, pH and EC) conditions (Rate et al. 2003, Sort and Alcaniz 1999, Adriano 2001). Reid and Naeth (2005b) found sewage sludge significantly increased CEC and organic carbon of kimberlite tailings which lead to higher plant growth and shoot and root biomass.

Increasing soil TC influences the C:N ratio. An ideal C:N ratio for microbial respiration and decomposition is approximately 10:1 (Halvin et al. 1999). Topsoil treatments had a C:N ratio of approximately 20:1, which was lower than Fertilizer and no amendment treatments and was not substantially different from undisturbed topsoil which had a C:N ratio of 31:1 (Table 2.14). Addition of sewage and sludge to substrates lowered the C:N ratio to a more suitable 8:1 and 10:1, respectively (Table 2.14). A major limiting factor to nutrient cycling on disturbed lands is lack of N because it is often bound in organic compounds resulting in high C:N ratios and nitrogen immobilization (Schimel et al. 1996). Amendments such as fertilizer and sludge that are high in ammonium are beneficial for increasing nitrogen in the soil and thus decreasing the C:N ratio which is necessary for nitrification and mineralization.

Inorganic carbon (IOC) and total kjeldahl nitrogen (TKN) were not significantly different among treatments and were only slightly above detection limits in most cases (Tables 2.14 and 2.15). TKN was used to calculate the C:N ratio for all treatments and was less than 0.001 at 20 to 30 cm.

4.2.6 Metals

Heavy metal concentrations for 11 (Sb, Be, Cd, Pb, Hg, Mo, Se, Ag, Tl, Sn and U) of the 19 metals analyzed were below detection limits and therefore likely pose little environmental concern. The remaining eight metals (As, Ba, Cr, Co, Cu, Ni, V and Zn) were present in the soil. No environmental quality guidelines have been developed for arctic soils. Therefore to determine if metal concentrations were elevated, they were compared to several references, including the abundance of metals found in the earth's Precambrian crust, Undisturbed Topsoil from East Island of Lac de Gras and to the Canadian Council of Ministers of the Environment (CCME) agricultural soil quality guidelines (2003). The abundance of metals found in the earth's Precambrian crust serves as a reference to which metals should be found in soil that has developed from a granite parent geological material. The undisturbed topsoil from East Island of Lac de Gras provides insight into the concentration of metals naturally found in the area, and the CCME guidelines give an approximate level that may be considered hazardous to the environment.

Concentrations of As, Ba, Cu and V were all lower than the CCME guidelines (Table 2.16) at the 0 to 10 cm depth increment. Similar trends were found for 20 to 30 cm for all metals analyzed (Table 2.17). Arsenic was approximately equivalent to that in crustal abundance and undisturbed topsoil concentrations for all treatments. Barium was well below CCME guidelines and crustal abundance for all treatments, however, Ba in PK treatments were substantially higher (approximately 6 times higher) than in undisturbed topsoil. Due to Ba being elevated in PK, treatments composed of a mixture of PK and Till (i.e., 50/50 and 25/75 treatments) were also higher in Ba than undisturbed topsoil. Copper was below CCME guidelines and crustal abundance values and equivalent to undisturbed topsoil for all treatments except Till Sewage, which was elevated to 90 mg/kg.

Chromium was elevated in PK and Sludge treatments to as high as 400 mg/kg, which is greater than CCME guidelines, crustal abundance and Undisturbed Topsoil values (Figure 2.7). 50/50 and 25/75 treatments were also elevated in Cr due to PK. Sludge treatments had higher concentrations of Cr than the other amendment treatments for that substrate. For example, 25/75 Sludge had a Cr concentration of 249 mg/kg, whereas 25/75, 25/75 Fertilizer and 25/75 Topsoil have Cr concentrations of 151.7 mg/kg, 215.3 mg/kg and 36.9 mg/kg, respectively. Chromium has been found in kimberlite material at other mine sites and was not taken up by plants or leached (Stevens 2006), therefore elevated concentrations will not likely hinder plant growth or create negative environmental impacts.

Nickel showed a similar trend in that PK and sludge treatments were elevated to as high as 1493 mg/kg, which is greater than CCME guidelines, crustal abundance and undisturbed topsoil values (Figure 2.8) and consequently so are values in 50/50 and 25/75 treatments. Similarly, Co concentrations in PK treatments were elevated beyond CCME guidelines, crustal abundance and undisturbed topsoil values (Figure 2.9) and consequently Co concentrations in 50/50 and 25/75 treatments were as well. Sewage treatments had Zn concentrations greater than CCME guidelines, crustal abundance and undisturbed topsoil values (Figure 2.10), however, the rest of the treatments were equivalent and below.

Soils developed from ultrabasic rocks are usually enriched in Cr, Co, Ni and Zn (Anderson et al. 1973, Adriano 2001), therefore soils derived from kimberlite will be elevated in these elements. Baker et al. (2001) found Diavik kimberlite was dominated by Si, Mg and Fe and the most abundant trace elements were Ni, Cr, Co, Sr and Zn. Although elements such as Cr, Co, Ni and Zn are considered essential micronutrients in low concentrations, at high concentrations they can be toxic to plants, animals and humans. In soils, most heavy metals occur as trace impurities within the crystal structure of primary and secondary minerals, inorganic compounds or are bound to organic matter, clays or hydrous oxides of Fe, Mn and Al (Foy et al. 1978). With precipitation and sorption of most metals by soil, the only metals of concern are Zn and Ni because plant toxicities frequently occur when they are present. Toxicologically, Zn is relatively inconsequential since there is a wide range between usual environmental and toxic concentrations (Adriano 2001). Although Ni was above CCME guidelines it is likely complexed with various organic and inorganic ligands in the Ni(II) form which is stable over a wide range of pH and redox conditions and unavailable to plants and therefore not a problem. For a metal to be assimilated, it would have to be mobile and transported and be bioavailable to plants. Zn and Ni are likely incorporated in the organic material in the soil, and are not dissolved in soil solution, sorbed onto exchange sites or in the free ionic or complexed form and thus are not bioavailable.

Toxicities of Co only occur under very unusual conditions and Cr is not phytotoxic in soils even at high levels (Adriano 2001). As long as pH remains relatively high in the soil, Cr will remain in trivalent form, which is less toxic to plants and less mobile in surface and subsurface environments than the hexavalent form. Similarly, Co is less available for uptake by plants at higher soil pH. No research has been conducted on effects of these metals on plant species growing in the arctic, therefore it is difficult to determine how these metals will affect long term revegetation success.

4.3 Vegetation

4.3.1 Plant density and species richness

Although there were no statistically significant differences between spring and fall seeding, in general spring seeding had a higher plant density than fall seeding with the exception of the Topsoil treatment (Figures 2.11, 2.12 and Table 2.18). Overall density and richness (for all treatments) were higher with spring than fall seeding. The difference in density and species richness between spring and fall seeding was largely due to seeding conditions. In fall, there were fewer days with wind speeds below 5 m/s, therefore seeds were often blown off site (Table 2.3). Microsites become very important when fall seeding because they allow seeds to be protected from the wind (Figure 2.15). The higher density in fall seeded Topsoil (151.8 plants/m^2 for PK Topsoil fall seeding vs 86.7 plants/m^2 for PK Topsoil spring seeding) treatments could be due to increased number of various sized rocks providing microsites.

Observational analyses showed microsites were important for all substrates, regardless of season of seeding. Consistent with previous research in arctic and alpine environments this research shows plants emerged and performed better when they germinated near a rock or crevice (Chambers 1995a and Chambers 1995b). Although, observed differences between spring and fall seeding could be due to the amount of time species have had to establish and grow (1 season for fall seeded G-A, adaptable, esker and no seed plots and 2 seasons for spring seeded plots) and the effect could decrease over time.

Topsoil treatments had the highest density and species richness (151.8 plants/m^2 and 13.7 species/m^2 , respectively). Treatments fertilized in 2005 had similar results to spring seeding. Fall seeded plots with the exception of Grasses and Forbs mixes did not receive fertilizer until 2006, therefore fall seeded Fertilizer treatments had lower densities and species richness (Figures 2.13, 2.14 and Table 2.18). Till, Till Topsoil, 50/50

Fertilizer and Gravel Fertilizer had significantly higher densities with spring than fall seeding. Density in the 50/50 Sewage treatment was higher with fall seeding than spring. Treatments with lowest plant densities were PK and 50/50 Sewage. The unexpected low density in the 50/50 Sewage treatment could be attributed to the raw sewage being applied too thick and not incorporated well enough in spring 2005, as well as the elevated Zn, SAR, EC and available P. Sewage treatments with stockpiled sewage that was more heterogeneous and mixed with gravel had higher plant densities than treatments that received sewage that had not been stockpiled and was seeded directly after application.

There were no statistically significant differences among spring seeded treatments for density or species richness (Table 2.18). Fall seeded treatments had significantly higher densities and richness in PK Topsoil and Gravel Topsoil treatments, respectively. For both spring and fall seeded treatments lowest densities occurred in PK and PK Fertilizer treatments and lowest species richness occurred in 25/75 Fertilizer, PK and PK Fertilizer treatments. There were no statistically significant differences for density or species richness among 25/75, 50/50, Gravel and Till treatments for any amendment.

4.3.2 Individual species response

Grass species with the greatest densities (>10 plants/m^2) in all treatments with both spring and fall seeding included *Festuca saximontana* (0.7 to 32 plants/m^2), *Agropyron violaceum* (1.7 to 29.3 plants/m^2) and *Poa glauca* (1.0 to 52.3 plants/m^2) (Table 2.19). Other grass species that performed well (density > 4 plants/m^2) included *Agrostis scabra* (0.3 to 12.3 plants/m^2), *Agropyron pauciflorum* (0.3 to 13.3 plants/m^2), *Poa alpina* (0.3 to 13.3 plants/m^2), *Arctagrostis latifolia* (0.3 to 7.7 plants/m^2) and *Deschampsia caespitosa* (0.7 to 7.3 plants/m^2). Out of the five seeded legumes, *Hedysarum mackenzii* had the greatest density (0 to 11.3 plants/m^2) (Table 2.20). Species with poor establishment included *Puccinellia nuttalliana, Epilobium latiofolium, Empetrum nigrum, Arctostaphylos rubra, Ledum decumbens, Loiseleuria procumbens,* and *Betula glandulosa.*

Species that emerged from the topsoil seed bank included *Vaccinium uliginosum* (Bog bilberry), *Betula glandulosa, Carex* sp., *Vaccinium vitis-idaea* (Mountain cranberry), *Arctostaphylos rubra* and *Rubus chamaemorous* (Cloudberry) (Table 2.20).

Species such as *Calamagrostis canadensis, Festuca rubra* and *Agropyron pauciflorum* that were considered aggressive and were removed from the G-A mix did not establish as well as expected, and had low densities on all treatments. These species were considered aggressive in more temperate environments such as Alberta where they are strong competitors for soil water and nutrients (Hardy BBT Ltd. 1989, Powell and Bork 2004), however did not appear to have a competitive advantage in the sub-arctic.

4.3.3 Seed mix response

Not all treatments had significant responses among seed mixes (i.e. treatments: 25/75 Fertilizer, 25/75 Topsoil, 50/50 Fertilizer, 50/50 Sewage, Gravel Fertilizer, PK, PK Fertilizer, PK Topsoil, PK Sludge and Till had no significant differences among seed mixes) (Table 2.21 and 2.22). With both spring and fall seeding the seed mixes with the highest densities included Esker (1 to 27.2 plants/m^2), G-A (1 to 33.3 plants/m^2) and Grasses (1 to 44.7 plants/m^2) mixes. These mixes contained three grasses, *Poa glauca, Festuca saximontana* and *Agropyron violaceum,* which had the greatest total density over all treatments. These species were seeded at a higher rate in the Esker mix due to fewer species being included in the mix, therefore plant density was higher in the treatments seeded with the Esker mix. Density in the Forbs mix was significantly lower than in the Esker, G-A and Grasses mixes in the 25/75, 25/75 Sludge, 50/50 Topsoil, Gravel Topsoil and Till Fertilizer treatments, due to lower seeding rates and less available seed.

No significant differences were found among treatments for seed mixes (density) with either spring or fall seeding, with the exception of fall seeded G-A mix which had a higher density in Gravel Topsoil than 25/75 Topsoil, 50/50, PK, PK Fertilizer and 50/50 Sewage treatments (Table 2.22). Although there was no significant difference with spring and fall seeding for the overall treatment densities per seed mix, seed mixes responded differently to individual treatments. The Grasses mix had a significantly higher density when it was seeded in fall on 50/50 and 50/50 Sewage treatments. Density for the G-A mix was higher when seeded in fall on 50/50 Topsoil, Gravel Topsoil, PK Topsoil and Till Fertilizer treatments. Forb density was higher when seeded in fall on Till and Till Topsoil treatments, and higher on Gravel Fertilizer when seeded in spring. When seeded with the Adaptable mix, 25/75 Topsoil, 50/50 Topsoil, Till Topsoil, 25/75 Fertilizer, 50/50 Fertilizer, Till Fertilizer and 50/50 Sewage had significant differences with spring and fall seeding. The Esker mix had significant differences with spring and fall seeding on 25/75 Topsoil, 50/50 Topsoil, 25/75, 50/50 Fertilizer, Gravel and Gravel Fertilizer treatments. Although not statistically significant, overall density with spring seeding was greater than with fall seeding for the three mixes that performed the best (Table 2.22).

4.3.4 Plant health and height

At the time of the 2006 assessment, the only plants that were not given a health value of 4 were those that had been grazed by wildlife. Plant height differed by species depending on growth habit and form (Appendix A). The majority of the plants were between 0 and 10 cm. However, grass species such as *Agropyron violaceum, Arctagrostis latifolia, Agrostis scabra* and *Poa glauca* reached heights of >20 cm, and forb species such as *Hedysarum mackenzii* and *Epilobium latifolium* reached heights between 10 and 20 cm. Grass and forb species were taller on treatments such as Block 2 Spring 50/50 Sewage which received the 2004 sewage that had been stockpiled over winter and was mixed with gravel and thus more heterogeneous (Figure 2.17 a and b). Grass and forb species were taller on Topsoil and Fertilizer treatments than on treatments with no amendment likely due to increased nutrients.

4.4 Reclamation Applications

Consistent with previous research (Bishop et al. 2001, Reid and Naeth 2005a, Stevens 2006), this study has shown that waste materials from the diamond mining process can be used to successfully establish native plant communities under field conditions. A direct relationship between soil treatment and plant establishment was found. Treatments that most closely resembled the undisturbed topsoil and were similar in texture, water holding capacity, nutrients, organic matter and pH had the highest plant densities. Treatments that best created these soil properties were 50/50 Topsoil and Till Topsoil. Since topsoil available for use in reclamation is limited, making use of other soil substrates and amendments is necessary for successful reclamation. The substrates and amendments that show promise for reclamation are 50/50, 25/75, Topsoil, Sewage and Fertilizer.

Without amendments, processed kimberlite and glacial till provided few benefits for plant establishment. PK had a sandy texture, low water holding capacity and low TC, and higher pH, EC, K, S, Mg, Na, Cr, Ni, Co and Zn compared to undisturbed topsoil. It also had the lowest plant density. Till had low CEC, TC and plant density. The texture of the till substrate was improved by the addition of PK. Without the sandy textured PK material, glacial till is likely to settle with time causing an increase in bulk density, and making it more unsuitable for plant roots. The addition of topsoil and fertilizer amendments resulted in plant densities similar to other treatments and thus makes both these substrates acceptable for reclamation with appropriate amendment. Although plant density and richness on Gravel, Gravel Topsoil and Gravel Fertilizer treatments were not significantly different from 25/75, 50/50 or Till treatments, further monitoring is necessary to determine if they are sustainable due to low water holding capacity, organic matter and nutrients. The use of gravel as a substrate for reclamation should be avoided until it is determined whether it can support a plant community over time.

There were no significant differences between 25/75 and 50/50 treatments for soil properties and vegetation response. Although they were slightly elevated in the same nutrients and metals as processed kimberlite, concentrations were not high enough to negatively influence plant growth. Therefore either substrate treatment is acceptable for reclamation.

Although topsoil, fertilizer and sewage amendments may require different management, they are all acceptable for use in reclamation. Nutrients (N, P, K, S) among substrates varied little after the addition of topsoil, sewage or inorganic fertilizer, with the exception of sewage increasing P and S. CEC was higher in topsoil and sewage amended treatments, therefore nutrient availability should be more sustainable. Topsoil amended treatments had a sandy loam texture, increased TC and CEC, decreased pH, low Cr, Ni, Co, and Zn concentrations compared to other treatments and the highest plant densities and species richness. Fertilizer amended treatments had similar plant densities and species richness, however TC, CEC and pH were unaffected. Therefore fertilizer amended substrates could require addition of soil building amendments for long term sustainability.

Sewage increased water holding capacity, organic matter and nutrients, which are beneficial for plant growth. However, EC, P, S, Na and Zn also increased, which may have negatively impacted plant establishment and growth and resulted in low plant densities. Plant densities were higher on treatments that received sewage that had been stockpiled over winter and mixed with gravel. Fecal coliform counts were lower in sewage stockpiled over winter, therefore winter sewage stockpiling can be an effective way to reduce the risk of pathogens entering surface or groundwater from reclamation sites and they can increase plant establishment. Plant response to sludge was variable, and although high ammonium concentration reduced the C:N ratio which is beneficial for mineralization and decomposition, increased S, Na, Cr and Ni concentrations could cause plant toxicity in the future. Thus, the use of sludge as a nutrient improving amendment for reclamation requires further investigation.

Microsites which act as wind breaks and are conducive for trapping seeds and water are advantageous because they create a more suitable environment for seed germination and establishment and should be created as much as possible on reclamation surfaces. This is critical due to limitations imposed on establishing plants from the harsh arctic climate. Microsites were increased on Till, 50/50, 25/75, Gravel and Topsoil, which resulted in increased surface variability, seed germination and plant establishment and success.

Plant density was highest in the Esker, Grasses and G-A spring seeded plots. The increased density in these seed mixes was due to the presence of grasses *Festuca saximontana, Agropyron violaceum* and *Poa glauca* which established most frequently on all treatments and therefore should be included in reclamation mixes. Grass species *Puccinellia nuttalliana*, forb species *Epilobium latifolium* and wild collected species *Betula glandulosa*, *Empetrum nigrum, Arctostaphylos rubra, Ledum decumbens and Loiseleuria procumbens* did not establish on most plots. Including these species in the seed mix is important to create an environment that closely resembles the undisturbed tundra, therefore methods to get these species to establish should be investigated. Spring seeding was more successful than fall seeding, for most treatments (exceptions include Gravel Topsoil, Till Topsoil, 50/50 None and 50/50 Sewage). Fall seeding was difficult due to high wind speeds and unpredictable weather, therefore, spring seeding should be employed whenever possible.

5.0 CONCLUSIONS

- Waste materials from the diamond mining process can be used to successfully establish native plant communities under field conditions.
- Without amendments, processed kimberlite and glacial till are unsuitable for plant establishment.
- Processed kimberlite and glacial till in combination with each other in 25/75 or 50/50 ratios and organic amendments are suitable for reclamation.
- Topsoil provides the most benefits for substrate enhancement and vegetation success and should be salvaged and used as an amendment whenever possible.
- Inorganic fertilizer results in equivalent vegetation success as topsoil, but did not enhance soil properties, therefore soil building amendments may also be required for long term sustainability.
- Sewage is a good source of organic matter and nutrients, however when applied as raw sewage at the rate in this study, it can be harmful to revegetation success. Lower rates and long term effects should be studied before ruling it out as an appropriate amendment.
- In general, spring seeding was more successful than fall, therefore seeding should be conducted in the spring whenever possible.
- Seed mixes for reclamation should include grass species *Festuca saximontana, Agropyron violaceum* and *Poa glauca* and forb species *Hedysarum mackenzii* as these species performed the best on all treatments.

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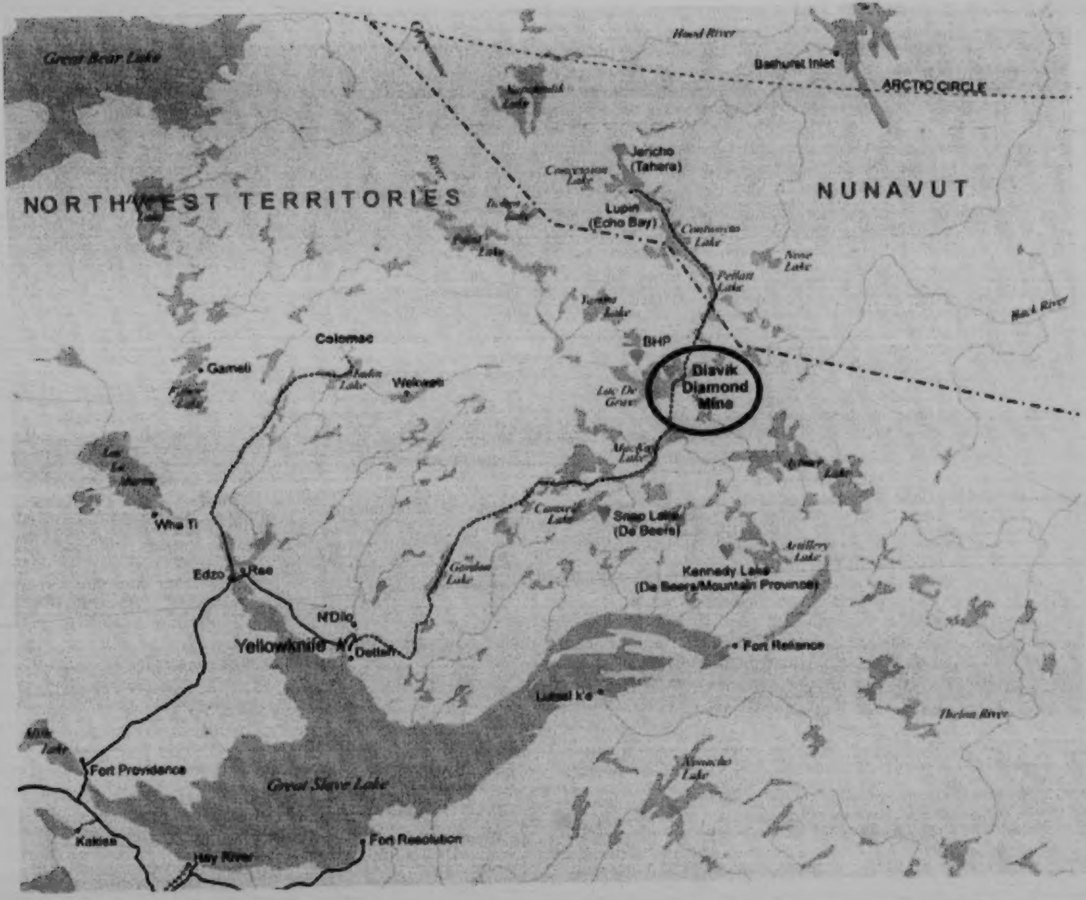

Great Bear Lake
Bathurst Inlet
ARCTIC CIRCLE
NORTHWEST TERRITORIES
NUNAVUT
Jericho
(Tahera)
Contwoyto Lake
Lupin
(Echo Bay)
Pellatt Lake
BHP
Diavik
Diamond
Mine
Lac De Gras
Colomac
Gameti
Wekweti
Wha Ti
Edzo
Rae
Snap Lake
(De Beers)
Kennedy Lake
(De Beers/Mountain Province)
Artillery Lake
N'Dilo
Yellowknife
Dettah
Fort Reliance
Lutsel K'e
Thelon River
Fort Providence
Great Slave Lake
Kakisa
Hay River
Fort Resolution

Figure 2.1. Location of Diavik Diamond Mine Inc. on East Island of Lac de Gras, NWT. (Adapted from Diavik Diamond Mines Inc. 2004).

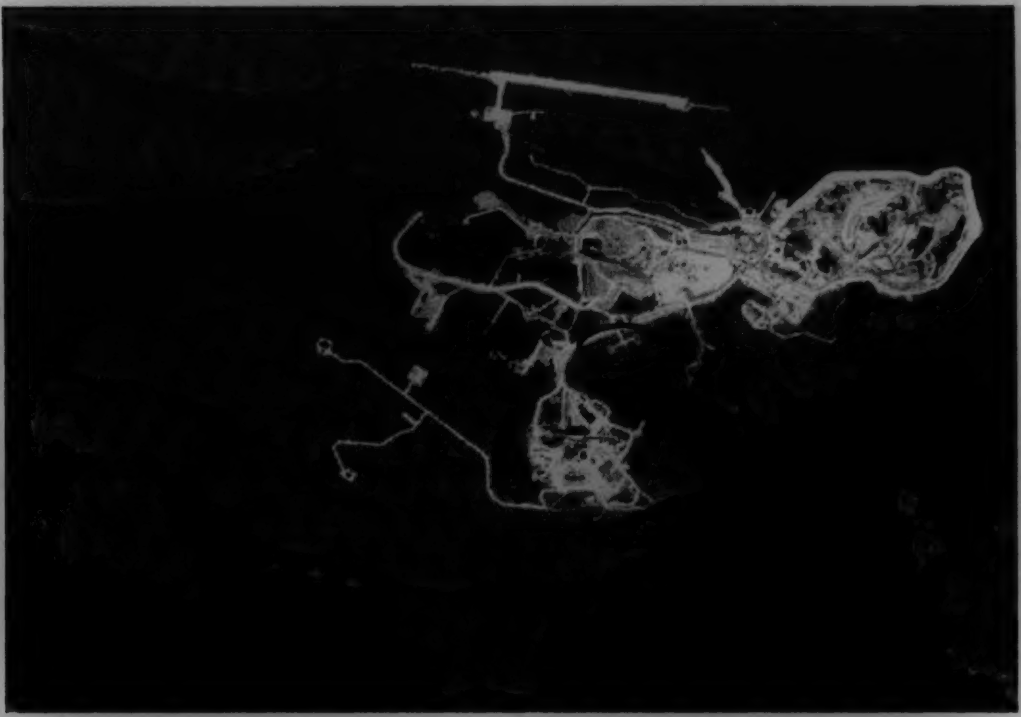
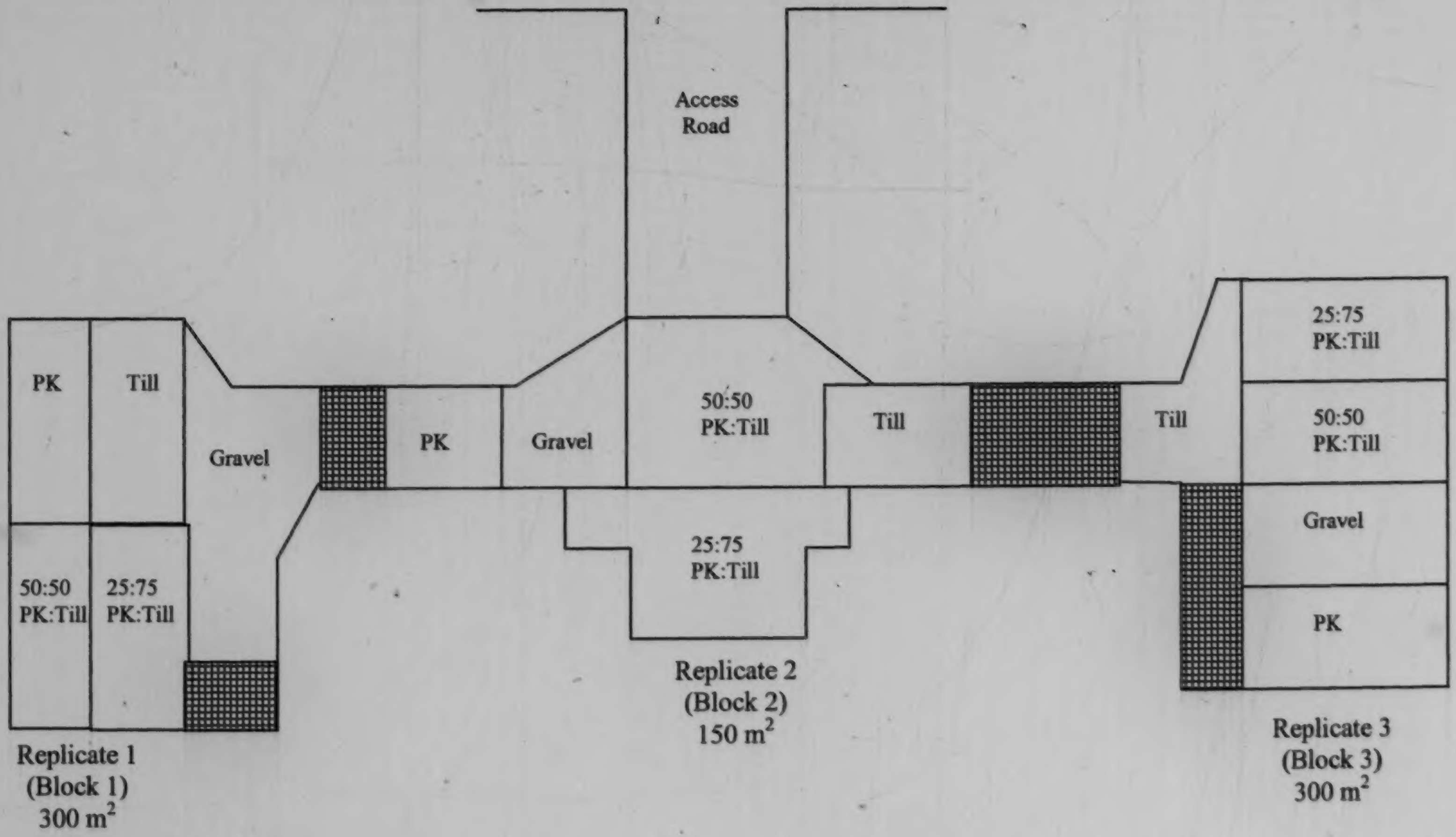


Figure 2.2. Location of the reclamation site on Diavik's abandoned ammonium nitrate storage area (shown in the circle). (Diagram courtesy of Diavik Diamond Mines Inc. 2004).


Access
Road
PK
Till
Gravel
50:50
PK:Till
25:75
PK:Till
PK
Gravel
50:50
PK:Till
25:75
PK:Till
Till
Till
25:75
PK:Till
50:50
PK:Till
Gravel
PK
Replicate 1
(Block 1)
300 m2
Replicate 2
(Block 2)
150 m2
Replicate 3
(Block 3)
300 m2

PK = Processed Kimberlite

Figure 2.3. Experimental design for the reclamation site at Diavik Diamond Mine, NWT.

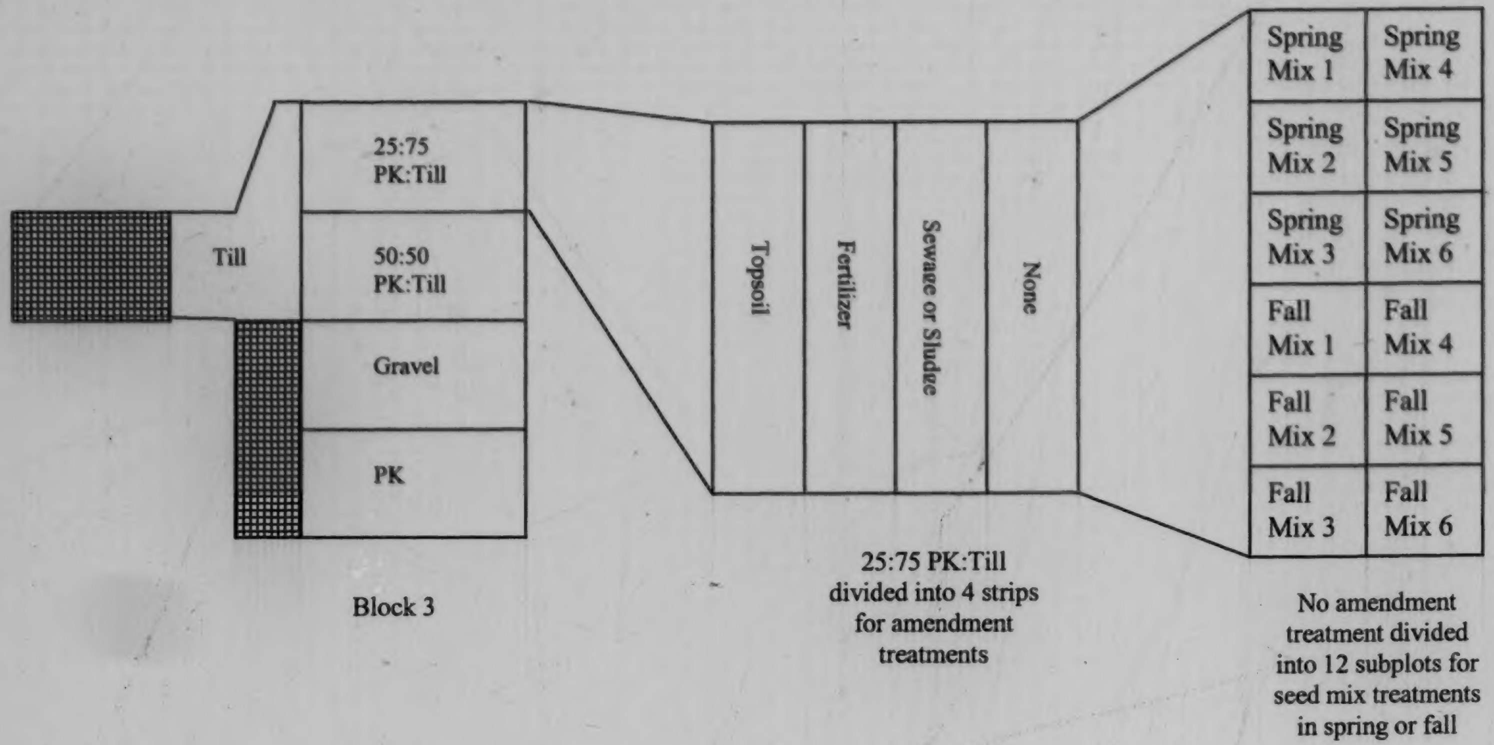

Till
25:75 PK:Till
50:50 PK:Till
Gravel
PK
Block 3
Topsoil
Fertilizer
Sewage or Sludge
None
25:75 PK:Till divided into 4 strips for amendment treatments
Spring Mix 1
Spring Mix 4
Spring Mix 2
Spring Mix 5
Spring Mix 3
Spring Mix 6
Fall Mix 1
Fall Mix 4
Fall Mix 2
Fall Mix 5
Fall Mix 3
Fall Mix 6
No amendment treatment divided into 12 subplots for seed mix treatments in spring or fall

Figure 2.4. Diagram of treatment divisions for the reclamation site at Diavik Diamond Mine, NWT.

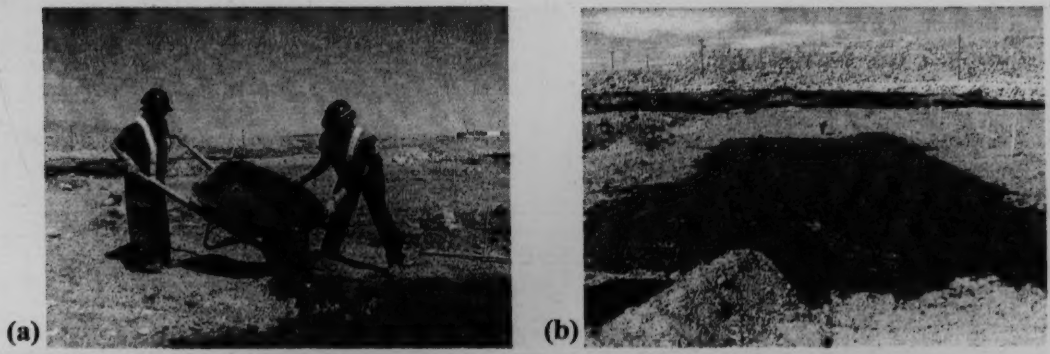


Figure 2.5. a) Sludge from the North Inlet Water Treatment Facility being applied to the 25/75 substrate, b) Sludge after being applied to the substrate at the reclamation site at Diavik Diamond Mine, NWT.

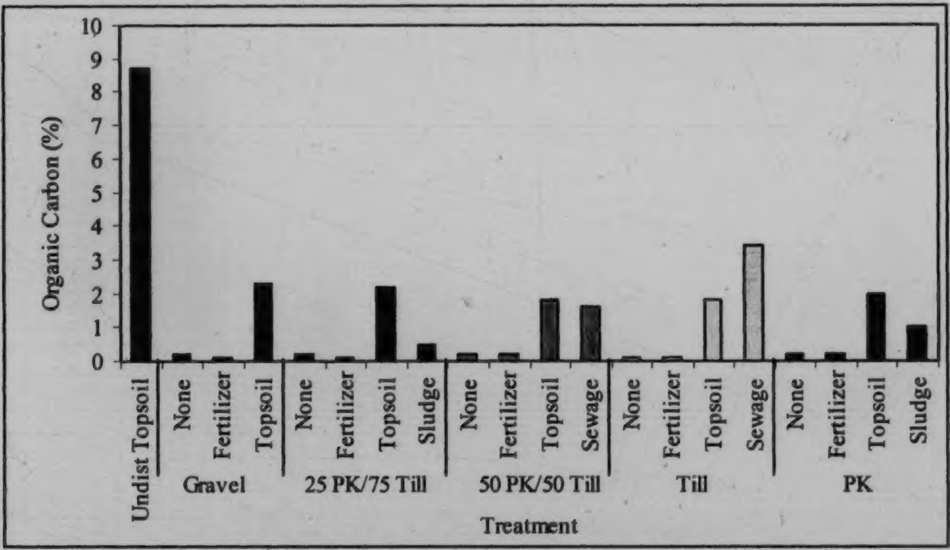


Figure 2.6. Total organic carbon content (0 to 10 cm) in substrate and amendment treatments for the reclamation site at Diavik Diamond Mine, NWT.

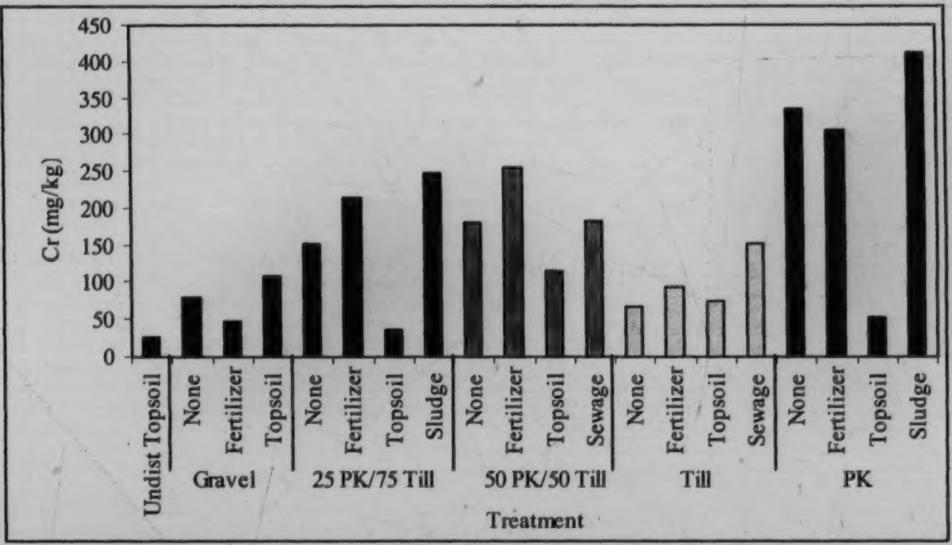


Figure 2.7. Chromium concentrations (mg/kg) (0 to 10 cm) in substrate and amendment treatments for the reclamation site at Diavik Diamond Mine, NWT.

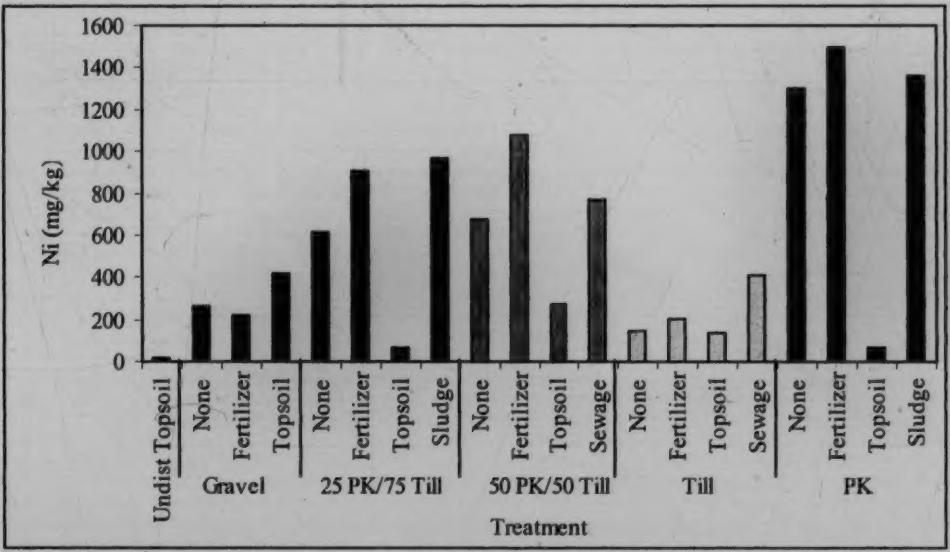


Figure 2.8. Nickel concentrations (mg/kg) (0 to 10 cm) in substrate and amendment treatments for the reclamation site at Diavik Diamond Mine, NWT.

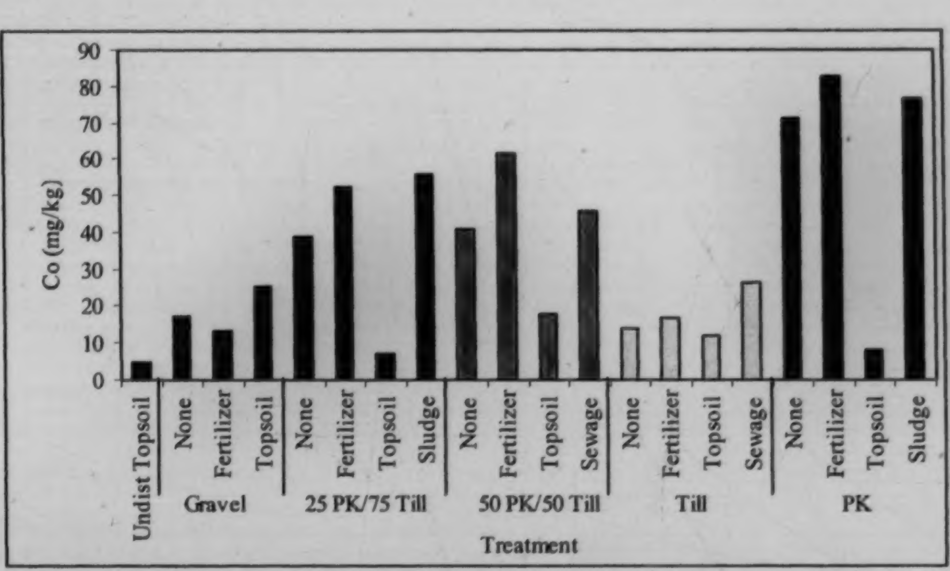


Figure 2.9. Cobalt concentrations (mg/kg) (0 to 10 cm) in substrate and amendment treatments for the reclamation site at Diavik Diamond Mine, NWT.

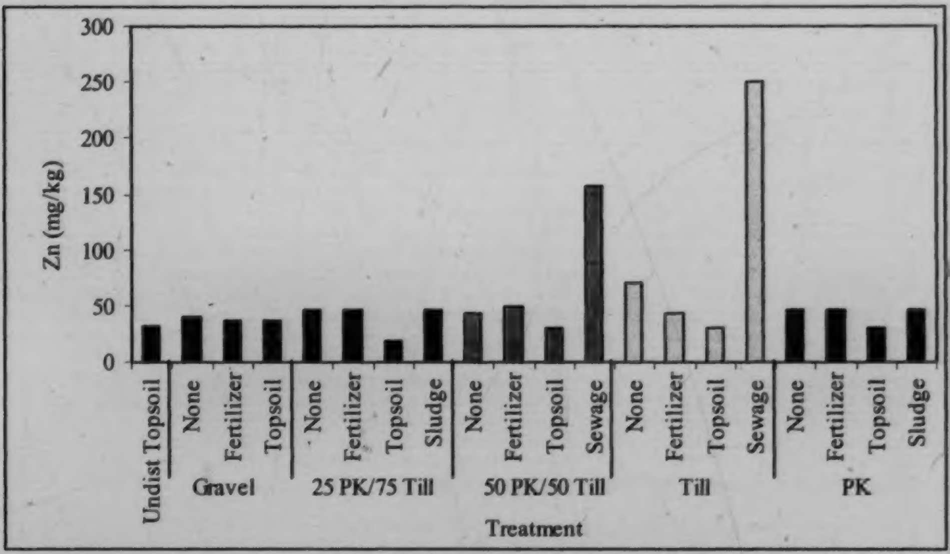


Figure 2.10. Zinc concentrations (mg/kg) (0 to 10 cm) in substrate and amendment treatments for the reclamation site at Diavik Diamond Mine, NWT.

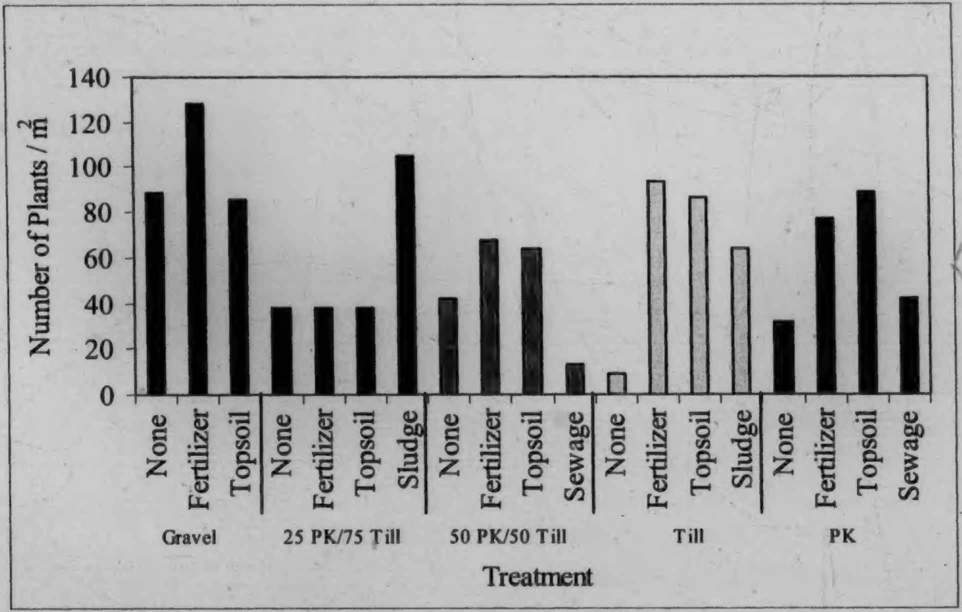


Figure 2.11. Plant species density for spring seeded treatments at the reclamation site at Diavik Diamond Mine, NWT.

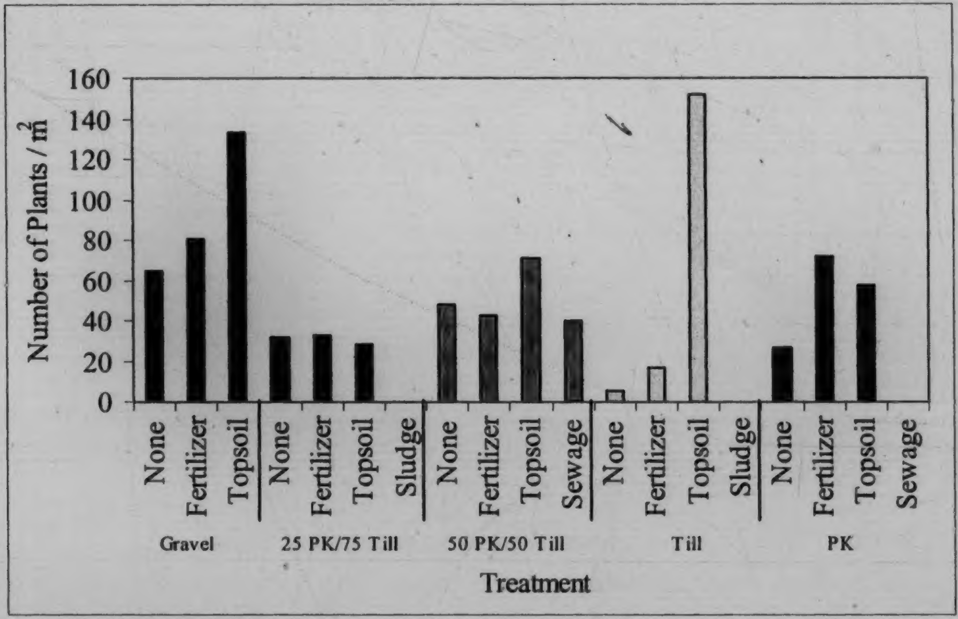


Figure 2.12. Plant species density for fall seeded treatments at the reclamation site at Diavik Diamond Mine, NWT.

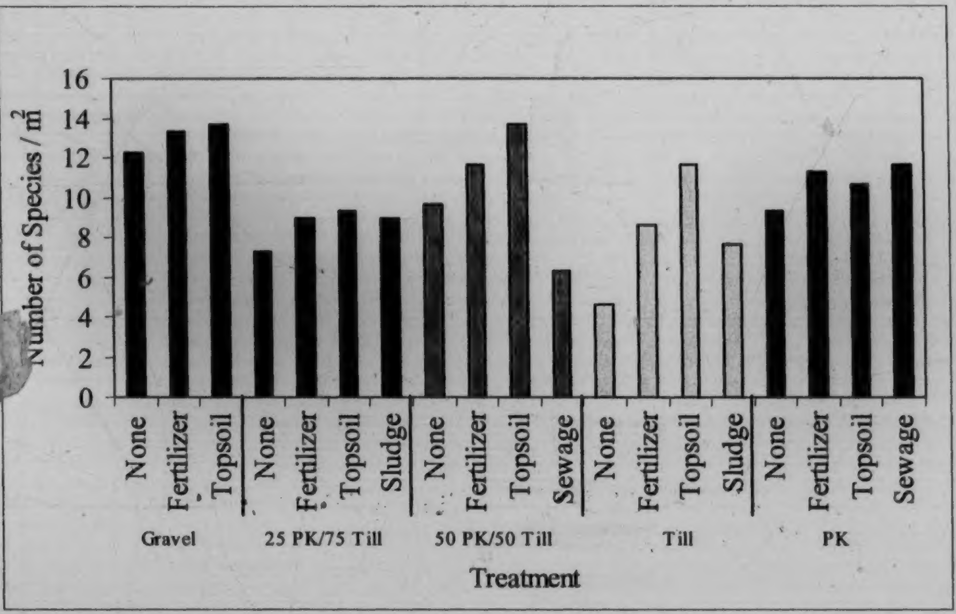


Figure 2.13. Plant species richness for spring seeded treatments at the reclamation site at Diavik Diamond Mine, NWT.

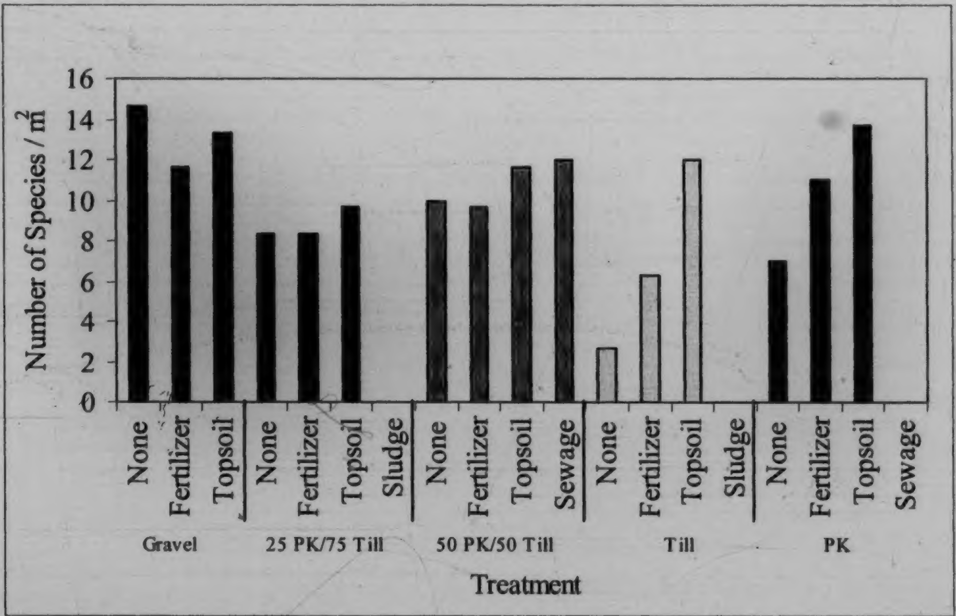
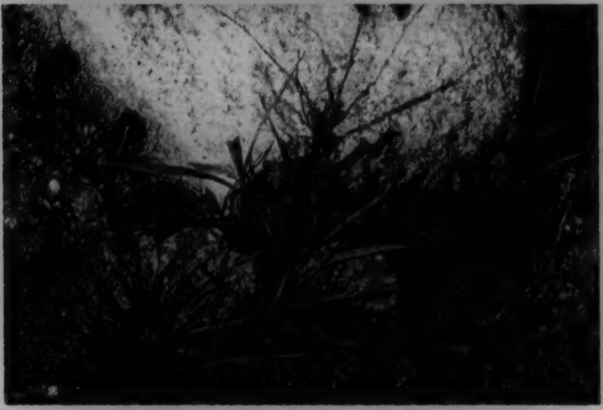


Figure 2.14. Plant species richness for fall seeded treatments at the reclamation site at Diavik Diamond Mine, NWT.

(a) Block 2 50/50 Sewage Spring depicting low plant density.

(b) Block 2 Till Sewage Spring depicting high plant density and tall plants.



(c) Block 2 50/50 Topsoil depicting the importance of microsites.

Figure 2.15. Photos taken at the reclamation site at Diavik Diamond Mine, July 2006.

Table 2.1. Seed mixes for reclamation at Diavik Diamond Mine, NWT.

Mix Name	Mix Description
Seeded In All Blocks	
Grasses	*Arctagrostis latifolia*, *Agrostis scabra*, *Agropyron violaceum*, *Agropyron pauciflorum*, *Calamagrostis canadensis*, *Deschampsia caespitosa*, *Festuca rubra*, *Festuca saximontana*, *Poa alpina*, *Poa glauca*, *Puccinellia nuttaliana* (11 grasses)
Forbs	*Hedysarum mackenzii*, *Hedysarum alpinum*, *Oxytropis splendens*, *Oxytropis deflexa*, *Epilobium latifolium* (5 forbs)
Grasses Without Aggressive Species	All grasses except *Festuca rubra*, *Calamagrostis canadensis*, *Agropyron pauciflorum* (8 species)
Adaptable	*Arctagrostis latifolia*, *Deschampsia caespitosa*, *Poa glauca*, *Festuca saximontana*, *Festuca rubra*, *Hedysarum mackenzii* (6 species)
Esker	*Poa glauca*, *Festuca saximontana*, *Agropyron violaceum*, *Poa alpina*, *Epilobium latifolium*, *Oxytropis campestris* (6 species)
No Seed	No seed added
Seeded In Blocks 1 and 3	
Wet Tundra	*Deschampsia caespitosa*, *Agrostis scabra*, *Puccinellia nuttalliana*, *Calamagrostis canadensis*, *Arctagrostis latifolia*, *Agropyron pauciflorum* (6 species)
Heath	*Arctagrostis latifolia*, *Calamagrostis canadensis*, *Poa alpina*, *Agropyron violaceum* or *pauciflorum*, *Oxytropis splendens* (5 species)
Wild Collected Seed	*Empetrum nigrum*, *Arctostaphylos rubra*, *Ledum decumbens*, *Loiseleuria procumbens*
Birch	*Betula glandulosa*

Table 2.2. Species used in the reclamation study at Diavik Diamond Mine, NWT.

Species Name	Common Name
Festuca rubra (L.) 'Arctared'	Red fescue
Poa glauca (Vahl) 'Tundra'	Glaucous bluegrass
Poa alpina (L.) 'Gruening'	Alpine bluegrass
Puccinellia nuttalliana (Schult)	Nuttall's alkali grass
Calamagrostis canadensis (Michx) Beauv.	Bluejoint
Arctagrostis latifolia (R.Br) 'Alyeska'	Polargrass
Festuca saximontana (Rydb.)	Rocky mountain fescue
Agrostis scabra (Wild.)	Tickle grass
Agropyron pauciflorum (Schwein) Hitchc.	Slender wheatgrass
Agropyron violaceum (Hornem.)	Alpine wheatgrass
Deschampsia caespitosa (L.) Beauv.	Tufted hairgrass
Hedysarum alpinum (L.)	Alpine hedysarum
Hedysarum mackenzii (Rich.)	Northern hedysarum
Oxytropis deflexa (Pall.)	Reflexed locoweed
Oxytropis splendens (Dougl. ex Hook.)	Showy locoweed
Oxytropis campestris (L.)	Northern yellow locoweed
Epilobium latifolium (L.)	Broad leaved willowherb

Table 2.3. Weather data from 1999 to 2006 for Diavik Diamond Mine, Lac de Gras, NWT.

Variable	1999	2000	2001	2002	2003	2004	2005	2006
Mean annual temperature (°C)	-7.4	-9	-8.5	-9.7	-8.7	-12	-8.1	n/a
Maximum annual temperature (°C)	27.2	27.3	25.8	25.7	25.9	25.3	25	19.2
Minimum annual temperature (°C)	-37	-41	-41.2	-44	-43	-41.3	-44	-40
Mean annual precipitation (mm)	n/a	n/a	311	352	322	275.1	133	n/a
Mean annual wind speed (m/s)	n/a	n/a	n/a	n/a	n/a	n/a	4	3.4
		2005			**2006**			
	June	**July**	**August**	**June**	**July**	**August**		
Mean growing season temp (°C)	6.5	11	10.2	11.2	12.5	12.2		
Total growing season precipitation (mm)	16	33.3	45	53.5	24.7	57.9		
Mean growing season wind speed (m/s)	3.7	3.5	3.9	3.9	3.4	3.7		

n/a = not available

Table 2.4. Particle size and texture (0 to 10 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	% Clay	% Sand	% Silt	Texture
25/75	Topsoil	4.0 (1.7)	78.7 (3.2)	17.3 (4.9)	Loamy Sand
50/50	Topsoil	5.0 (1.0)	76.7 (1.2)	18.3 (1.5)	Loamy Sand
Gravel	Topsoil	4.0 (1.0)	74.0 (5.3)	22.3 (4.0)	Loamy Sand
PK	Topsoil	5.7 (4.7)	68.0 (13.5)	26.7 (13.5)	Sandy Loam
Till	Topsoil	2.7 (1.5)	73.0 (3.2)	21.7 (1.2)	Sandy Loam
25/75	None	6.7 (3.1)	76.3 (7.4)	16.7 (4.6)	Sandy Loam
50/50	None	4.0 (1.7)	82.3 (2.5)	13.3 (2.1)	Loamy Sand
Gravel	None	2.5 (2.1)	86.7 (1.2)	12.0 (1.0)	Sand
PK	None	3.7 (1.5)	90.0 (2.0)	6.7 (2.3)	Sand
Till	None	6.0 (2.0)	68.3 (2.5)	26.7 (2.1)	Sandy Loam
25/75	Fertilizer	3.7 (1.2)	85.7 (2.1)	10.7 (2.5)	Loamy Sand
50/50	Fertilizer	5.3 (2.9)	84.0 (3.6)	10.7 (1.2)	Loamy Sand
Gravel	Fertilizer	2.3 (0.6)	82.7 (4.2)	14.7 (3.8)	Loamy Sand
PK	Fertilizer	4.0 (1.7)	88.7 (2.1)	7.3 (3.1)	Sand
Till	Fertilizer	6.0 (3.5)	70.0 (4.0)	24.0 (2.0)	Sandy Loam
25/75	Sludge	6.3 (4.5)	80.3 (6.7)	13.3 (4.6)	Loamy Sand
PK	Sludge	4.7 (0.6)	93.0 (1.7)	2.7 (1.5)	Sand
50/50	Sewage	5.3 (2.1)	80.7 (3.8)	14.0 (4.7)	Loamy Sand
Till	Sewage	8.3 (3.1)	69.0 (6.0)	22.7 (3.1)	Sandy Loam
Undisturbed Topsoil		5.5 (2.9)	64 (8.3)	31 (5.7)	Sandy Loam

PK = Processed Kimberlite

Values reported as Mean (Standard Deviation)

Table 2.5. Particle size and texture (20 to 30 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	% Clay	% Sand	% Silt	Texture
25/75	Topsoil	2.3 (0.6)	84.3 (3.2)	13.0 (3.5)	Loamy Sand
50/50	Topsoil	3.3 (1.5)	82.7 (3.5)	14.0 (4.6)	Loamy Sand
Gravel	Topsoil	2.3 (1.5)	83.7 (2.9)	14.0 (3.0)	Loamy Sand
PK	Topsoil	4.0 (2.6)	77.0 (11.4)	19.3 (9.0)	Loamy Sand
Till	Topsoil	5.3 (5.9)	74.7 (15.3)	19.7 (11.0)	Sandy Loam
25/75	None	3.3 (4.0)	81.0 (12.8)	16.3 (8.5)	Sandy Loam
50/50	None	4.0 (1.7)	80.7 (3.5)	15.7 (2.1)	Loamy Sand
Gravel	None	1.0 (0.0)	87.0 (2.6)	12.3 (2.1)	Sand
PK	None	3.3 (1.5)	89.7 (2.1)	7.0 (2.0)	Sand
Till	None	5.7 (3.2)	68.7 (9.0)	26.0 (6.6)	Sandy Loam
25/75	Fertilizer	2.3 (1.2)	85.0 (5.2)	12.3 (5.1)	Loamy Sand
50/50	Fertilizer	3.0 (1.7)	83.3 (5.1)	13.7 (3.5)	Loamy Sand
Gravel	Fertilizer	1.7 (0.6)	86.0 (2.0)	13.0 (1.0)	Sand
PK	Fertilizer	3.7 (1.5)	89.3 (1.2)	7.3 (1.5)	Sand
Till	Fertilizer	4.3 (3.2)	71.7 (3.5)	24.0 (1.0)	Sandy Loam
25/75	Sludge	8.0 (5.6)	73.0 (13.0)	19.0 (7.5)	Sandy Loam
PK	Sludge	4.7 (1.5)	91.3 (2.1)	4.0 (1.0)	Sand
50/50	Sewage	3.2 (1.9)	83.9 (3.0)	12.8 (2.1)	Loamy Sand
Till	Sewage	8.0 (4.6)	68.0 (6.1)	24.3 (3.2)	Sandy Loam
Undisturbed Topsoil		5.5 (2.9)	64 (8.3)	31 (5.7)	Sandy Loam

PK = Processed Kimberlite

Values reported as Mean (Standard Deviation)

Table 2.6. Soil temperature (°C) (0 to 10 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		June 2005			July 2005			August 2005			June 2006			July 2006			August 2006		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	12.1	21.7	4.2	13.4	25.7	6.2	10.9	24.7	2.6	17.4	28.8	7.6	15.1	29.3	6.4	14.0	28.2	4.4
50/50	Topsoil	11.6	20.4	4.7	13.0	23.0	6.5	10.6	19.3	3.3	16.7	25.9	8.7	14.7	26.6	7.1	13.5	25.1	4.9
Gravel	Topsoil	10.3	19.4	3.7	12.5	19.5	6.6	10.4	21.0	3.4	16.1	24.0	9.0	14.4	25.6	7.3	13.5	24.9	4.9
PK	Topsoil	12.4	21.5	4.3	13.5	25.6	6.5	11.5	24.7	2.8	17.3	28.3	8.3	15.3	28.7	6.6	13.9	27.7	3.6
Till	Topsoil	10.7	17.8	5.0	12.3	21.1	6.5	10.1	19.6	3.4	15.7	23.2	8.2	14.0	24.6	7.1	13.1	23.8	4.8
25/75	None	12.3	20.5	5.3	13.5	24.3	6.4	10.9	23.3	3.2	17.3	26.6	9.0	15.1	27.9	7.2	14.0	27.0	4.6
50/50	None	11.6	18.9	6.0	13.3	22.4	7.2	10.9	20.9	4.1	16.3	23.1	9.8	15.0	25.0	8.6	14.2	24.5	5.6
Gravel	None	10.7	17.1	3.3	12.0	23.3	4.7	9.6	22.0	1.7	15.4	25.7	6.0	13.3	26.2	5.3	12.2	25.6	3.0
PK	None	13.0	19.3	7.6	14.3	23.6	8.2	11.6	21.5	4.5	18.6	28.3	10.5	16.6	29.4	8.1	15.0	28.7	5.0
Till	None	11.1	18.7	5.3	12.6	21.7	6.4	10.2	20.3	3.5	17.0	26.5	8.3	14.7	27.3	6.6	13.7	27.1	4.5
25/75	Fertilizer	12.4	20.6	5.5	13.6	24.1	6.8	11.0	22.8	3.4	17.4	26.5	9.1	15.0	27.3	7.3	13.8	26.6	4.7
50/50	Fertilizer	12.3	20.8	5.5	13.5	24.0	6.6	10.9	22.1	3.4	16.6	24.8	9.0	14.9	26.1	7.5	13.8	25.4	5.0
Gravel	Fertilizer	10.1	16.5	5.2	12.0	20.5	6.3	10.2	18.3	3.6	15.6	23.5	8.3	14.1	24.3	7.4	13.0	21.7	4.8
PK	Fertilizer	12.7	19.1	7.0	14.1	23.5	8.0	11.6	21.8	4.5	15.9	24.0	9.1	15.7	26.9	8.5	13.4	25.5	4.8
Till	Fertilizer	11.3	19.3	5.1	12.8	22.3	6.2	10.4	20.7	3.2	16.7	26.1	7.7	14.7	27.6	6.3	13.6	27.0	4.3
25/75	Sludge	14.4	22.3	9.5	13.3	22.0	7.2	10.7	20.5	3.8	16.8	24.2	10.0	14.2	25.0	8.0	13.6	24.4	5.1
PK	Sludge	n/a	n/a	n/a	13.9	21.5	8.1	11.5	20.5	4.5	18.4	25.6	12.1	16.4	26.1	9.7	15.0	25.9	5.9
50/50	Sewage	10.8	18.3	5.4	12.7	23.1	6.8	10.8	13.2	11.0	15.7	23.5	8.7	14.8	24.8	8.1	13.8	26.2	4.6
Till	Sewage	13.7	18.6	8.7	12.6	21.1	6.8	10.4	19.8	3.7	16.1	23.0	9.1	14.1	24.2	7.7	13.1	23.2	5.1
Overall Mean		11.9	19.5	5.6	13.1	22.7	6.7	10.8	20.9	3.9	16.7	25.3	8.9	14.8	26.5	7.4	13.7	25.7	4.7

PK = Processed Kimberlite, sample size (n) = 3

Table 2.7. Soil temperature (°C) (20 to 30 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		June 2005			July 2005			August 2005			June 2006			July 2006			August 2006		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	9.7	14.0	6.5	12.1	17.7	8.1	10.4	16.4	5.1	15.5	19.0	11.4	14.1	20.9	9.6	13.4	20.6	6.3
50/50	Topsoil	9.8	14.7	6.2	11.8	17.5	7.4	9.9	16.1	4.6	14.8	18.6	10.4	13.5	20.7	12.9	12.8	20.0	5.9
Gravel	Topsoil	8.6	13.5	4.8	11.4	16.5	7.2	9.9	15.2	4.9	14.6	17.6	11.1	13.4	19.7	9.3	12.9	19.4	6.2
PK	Topsoil	9.5	15.7	6.8	11.8	16.9	8.1	10.4	15.7	5.4	14.7	17.5	11.6	13.8	19.5	10.0	13.0	21.6	13.0
Till	Topsoil	9.4	13.6	6.3	11.5	14.9	7.4	9.8	15.2	4.7	14.4	17.7	10.3	13.3	19.9	8.9	12.7	19.4	6.0
25/75	None	10.9	15.9	6.9	12.8	19.2	7.9	10.7	18.0	4.7	16.2	20.8	11.5	14.5	22.5	9.4	13.6	22.1	5.9
50/50	None	10.6	15.8	6.8	12.6	18.7	7.6	10.5	17.2	4.7	15.9	21.6	10.7	14.8	23.1	9.2	13.7	22.7	5.8
Gravel	None	9.8	14.5	6.3	11.8	17.9	7.1	10.1	16.1	4.5	15.0	19.0	10.6	13.7	20.6	9.2	12.9	20.3	5.8
PK	None	12.0	17.0	7.6	13.7	21.2	8.5	11.5	19.5	5.3	16.3	19.3	13.1	15.2	21.2	11.1	14.3	21.6	5.3
Till	None	10.5	16.8	5.7	12.2	19.8	6.8	10.1	18.4	3.9	15.3	19.2	11.0	13.6	20.8	8.9	12.9	20.7	5.8
25/75	Fertilizer	11.2	17.5	6.3	12.9	20.6	7.4	10.6	19.3	4.1	17.0	27.5	17.1	14.6	26.9	7.7	13.6	26.3	4.8
50/50	Fertilizer	10.4	15.4	6.8	12.4	18.1	7.8	10.5	16.7	5.0	15.2	18.7	11.0	14.2	20.7	9.7	13.4	20.5	6.4
Gravel	Fertilizer	10.5	19.8	3.9	12.1	22.4	5.2	10.2	20.8	2.6	14.9	20.5	9.1	13.6	21.7	8.3	12.8	21.2	5.4
PK	Fertilizer	11.9	17.3	7.4	13.6	21.4	8.3	11.4	19.6	5.1	13.4	16.4	10.8	14.2	19.2	10.4	12.6	18.3	6.8
Till	Fertilizer	10.6	15.5	5.4	12.3	20.3	6.6	10.1	18.9	3.8	15.2	19.7	10.3	13.8	21.6	8.6	13.1	21.3	5.6
25/75	Sludge	12.6	19.8	10.1	12.4	18.0	8.0	10.3	16.4	4.8	15.6	19.3	11.6	14.1	20.9	9.5	13.2	20.5	6.1
PK	Sludge	n/a	n/a	n/a	12.6	21.4	9.0	10.8	15.3	6.2	16.5	19.0	13.7	15.4	20.6	12.0	14.4	20.6	7.7
50/50	Sewage	9.2	13.2	6.5	11.7	17.3	7.8	10.2	11.0	9.5	14.1	17.2	9.6	13.8	19.4	10.1	13.1	20.1	6.1
Till	Sewage	11.1	19.3	9.1	11.3	16.0	7.5	9.8	14.7	5.0	13.8	16.9	10.2	12.6	18.8	8.7	11.9	17.9	5.6
Overall Mean		10.5	16.1	6.6	12.3	18.7	7.6	10.4	16.9	5.0	15.2	19.2	11.3	14.0	21.0	9.7	13.2	20.8	6.3

PK = Processed Kimberlite, sample size (n) = 3

Table 2.8. Soil water (m^3/m^3) (0 to 10 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		June 2005			July 2005			August 2005			June 2006			July 2006			August 2006		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	0.08	0.09	0.08	0.10	0.19	0.08	0.11	0.20	0.07	0.07	0.18	0.05	0.08	0.13	0.06	0.09	0.14	0.07
50/50	Topsoil	0.03	0.03	0.03	0.03	0.12	0.02	0.05	0.12	0.05	0.10	0.24	0.03	0.05	0.17	0.04	0.05	0.14	0.03
Gravel	Topsoil	0.02	0.03	0.01	0.02	0.06	0.01	0.03	0.09	0.02	0.09	0.02	0.09	0.08	0.05	0.09	0.08	0.02	0.09
PK	Topsoil	0.03	0.04	0.02	0.05	0.17	0.02	0.08	0.20	0.04	0.03	0.17	0.01	0.05	0.12	0.13	0.05	0.17	0.02
Till	Topsoil	0.03	0.03	0.03	0.04	0.20	0.03	0.06	0.23	0.03	0.08	0.27	0.05	0.08	0.20	0.05	0.08	0.25	0.05
25/75	None	0.08	0.09	0.06	0.10	0.19	0.07	0.12	0.25	0.06	0.03	0.08	0.05	0.04	0.05	0.05	0.03	0.10	0.06
50/50	None	0.08	0.10	0.08	0.10	0.19	0.05	0.10	0.23	0.08	0.08	0.18	0.07	0.08	0.12	0.07	0.09	0.17	0.06
Gravel	None	0.01	0.02	0.01	0.01	0.08	0.00	0.04	0.09	0.00	0.02	0.13	0.01	0.03	0.07	0.02	0.03	0.11	0.01
PK	None	0.09	0.11	0.08	0.10	0.15	0.08	0.11	0.16	0.09	0.10	0.17	0.09	0.11	0.06	0.09	0.10	0.15	0.08
Till	None	0.01	0.03	0.01	0.03	0.10	0.01	0.06	0.14	0.02	0.05	0.19	0.03	0.08	0.13	0.04	0.09	0.19	0.04
25/75	Fertilizer	0.04	0.05	0.04	0.05	0.11	0.04	0.08	0.17	0.02	0.07	0.24	0.04	0.07	0.12	0.05	0.10	0.21	0.05
50/50	Fertilizer	0.06	0.07	0.05	0.07	0.15	0.05	0.09	0.18	0.06	0.23	0.16	0.05	0.07	0.13	0.06	0.08	0.21	0.05
Gravel	Fertilizer	0.01	0.02	0.00	0.01	0.10	0.00	0.03	0.13	0.00	0.02	0.12	0.01	0.03	0.06	0.01	0.03	0.11	0.01
PK	Fertilizer	0.09	0.10	0.08	0.09	0.16	0.08	0.10	0.15	0.08	0.09	0.12	0.07	0.09	0.15	0.08	0.09	0.14	0.08
Till	Fertilizer	0.02	0.04	0.02	0.04	0.13	0.02	0.08	0.21	0.03	0.08	0.25	0.04	0.12	0.22	0.06	0.14	0.29	0.04
25/75	Sludge	0.05	0.06	0.07	0.06	0.15	0.04	0.16	0.28	0.06	0.09	0.29	0.05	0.16	0.25	0.07	0.11	0.26	0.06
PK	Sludge	n/a	n/a	n/a	0.14	0.18	0.00	0.15	0.20	0.11	0.10	0.21	0.08	0.09	0.12	0.08	0.09	0.17	0.08
50/50	Sewage	0.15	0.17	0.14	0.14	0.22	0.12	0.15	0.18	0.16	0.05	0.04	0.06	0.07	0.16	0.06	0.08	0.19	0.06
Till	Sewage	0.05	0.06	0.07	0.09	0.18	0.05	0.14	0.18	0.07	0.08	0.22	0.06	0.10	0.19	0.07	0.11	0.27	0.07
Overall Mean		0.05	0.06	0.05	0.07	0.15	0.04	0.09	0.18	0.05	0.08	0.17	0.05	0.08	0.13	0.06	0.08	0.17	0.05

PK = Processed Kimberlite, sample size (n) = 3

Table 2.9. Soil water (m^3/m^3) (20 to 30 cm) for soil treatments at the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		June 2005			July 2005			August 2005			June 2006			July 2006			August 2006		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	0.08	0.08	0.07	0.09	0.06	0.08	0.10	0.14	0.08	0.09	0.29	0.07	0.11	0.15	0.10	0.11	0.16	0.10
50/50	Topsoil	0.05	0.06	0.05	0.05	0.14	0.08	0.07	0.22	0.04	0.07	0.08	0.09	0.05	0.02	0.06	0.05	0.08	0.05
Gravel	Topsoil	0.04	0.00	0.05	0.00	0.01	0.01	0.01	0.04	0.01	0.00	0.11	0.01	0.00	0.03	0.01	0.00	0.04	0.01
PK	Topsoil	0.05	0.06	0.05	0.06	0.07	0.05	0.06	0.11	0.05	0.06	0.16	0.05	0.06	0.08	0.05	0.06	0.10	0.05
Till	Topsoil	0.06	0.07	0.05	0.07	0.20	0.05	0.10	0.23	0.06	0.07	0.24	0.05	0.08	0.20	0.07	0.08	0.21	0.05
25/75	None	0.07	0.07	0.06	0.07	0.11	0.06	0.09	0.15	0.05	0.08	0.18	0.06	0.06	0.10	0.05	0.06	0.14	0.04
50/50	None	0.38	0.09	0.07	0.09	0.11	0.08	0.11	0.19	0.08	0.09	0.25	0.08	0.07	0.10	0.06	0.07	0.13	0.06
Gravel	None	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.03	0.02	0.01	0.11	0.02	0.00	0.03	0.04	0.00	0.05	0.01
PK	None	0.08	0.10	0.08	0.09	0.12	0.08	0.10	0.15	0.09	0.09	0.24	0.08	0.09	0.11	0.08	0.05	0.12	0.03
Till	None	0.03	0.04	0.03	0.03	0.05	0.02	0.06	0.12	0.02	0.04	0.13	0.02	0.06	0.12	0.04	0.05	0.11	0.03
25/75	Fertilizer	0.06	0.06	0.05	0.06	0.07	0.05	0.08	0.15	0.05	0.07	0.27	0.06	0.08	0.12	0.06	0.08	0.16	0.07
50/50	Fertilizer	0.05	0.06	0.05	0.06	0.13	0.05	0.08	0.13	0.06	0.23	0.16	0.06	0.06	0.11	0.05	0.06	0.13	0.05
Gravel	Fertilizer	0.01	0.02	0.01	0.01	0.03	0.00	0.02	0.09	0.00	0.01	0.13	0.00	0.02	0.04	0.01	0.01	0.06	0.00
PK	Fertilizer	0.08	0.09	0.07	0.08	0.10	0.08	0.09	0.14	0.08	0.09	0.15	0.09	0.09	0.11	0.08	0.09	0.14	0.08
Till	Fertilizer	0.03	0.03	0.02	0.03	0.05	0.02	0.06	0.11	0.03	0.06	0.14	0.04	0.08	0.14	0.06	0.06	0.10	0.04
25/75	Sludge	0.04	0.05	0.08	0.06	0.09	0.05	0.16	0.32	0.05	0.13	0.35	0.10	0.19	0.24	0.09	0.12	0.25	0.08
PK	Sludge	n/a	n/a	n/a	0.09	0.12	0.03	0.10	0.18	0.07	0.06	0.27	0.05	0.07	0.12	0.06	0.07	0.14	0.06
50/50	Sewage	0.10	0.11	0.09	0.11	0.14	0.09	0.12	0.15	0.13	0.09	0.27	0.08	0.09	0.12	0.08	0.09	0.25	0.07
Till	Sewage	0.01	0.06	0.16	0.03	0.06	0.06	0.11	0.27	0.04	0.11	0.25	0.08	0.13	0.21	0.10	0.12	0.22	0.09
Overall Mean		0.07	0.06	0.06	0.06	0.09	0.05	0.08	0.15	0.05	0.08	0.20	0.06	0.07	0.11	0.06	0.06	0.14	0.05

PK = Processed Kimberlite, sample size (n) = 3

Table 2.10. Mean soil available nutrients (mg/kg) (0 to 10 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	Nitrogen	Phosphorus	Potassium	Sulfur
25/75	Topsoil	2.8 (0.7)	9.0 (0.7)^{b}	70.4 (17.0)^{c}	17.1 (3.0)^{c}
50/50	Topsoil	3.3 (2.6)	7.3 (2.2)^{b}	80.9 (22.6)^{c}	22.2 (18.6)^{bc}
Gravel	Topsoil	3.9 (1.7)	7.6 (0.5)^{b}	108.3 (56.2)^{c}	36.3 (1.2)^{bc}
PK	Topsoil	3.1 (1.5)	7.2 (1.8)^{b}	60.9 (17.5)^{c}	33.9 (41.2)^{bc}
Till	Topsoil	10.1 (9.3)	9.4 (3.7)^{b}	73.6 (13.2)^{c}	32.6 (9.3)^{bc}
25/75	None	6.4 (0.8)	4.7 (1.2)^{b}	148.2 (37.5)^{bc}	35.9 (10.8)^{bc}
50/50	None	6.2 (2.7)	3.9 (0.8)^{b}	194.0 (21.8)^{abc}	52.0 (6.4)^{bc}
Gravel	None	9.1 (6.3)	3.2 (1.7)^{b}	41.6 (18.4)^{c}	5.6 (1.3)^{c}
PK	None	3.6 (0.9)	1.7 (0.7)^{b}	332.8 (44.6)^{a}	99.8 (25.7)^{ab}
Till	None	8.6 (8.0)	7.3 (0.0)^{b}	61.3 (11.6)^{c}	19.4 (6.1)^{bc}
25/75	Fertilizer	38.6 (39.6)	15.0 (7.5)^{b}	183.4 (22.2)^{abc}	50.3 (3.0)^{bc}
50/50	Fertilizer	14.9 (19.7)	13.7 (0.6)^{b}	188.9 (39.0)^{abc}	42.1 (12.6)^{bc}
Gravel	Fertilizer	26.3 (43.3)	21.0 (14.5)^{b}	68.8 (34.7)^{c}	9.8 (3.5)^{c}
PK	Fertilizer	6.4 (3.2)	28.0 (16.1)^{b}	330.3 (22.4)^{a}	80.7 (12.1)^{ab}
Till	Fertilizer	54.1 (40)	13.7 (2.9)^{b}	72.8 (8.5)^{c}	21.4 (5.0)^{bc}
25/75	Sludge	16.1 (10.8)	5.8 (1.1)^{b}	198.7 (50.9)^{abc}	72.4 (35.4)^{b}
PK	Sludge	1.9 (0.5)	3.3 (0.9)^{b}	356 (29.1)^{a}	51.7 (20.0)^{bc}
50/50	Sewage	12.7 (7.2)	250.5 (74.8)^{ab}	307.5 (139.7)^{ab}	62.1 (14.7)^{bc}
Till	Sewage	34.0 (34.2)	487.5 (98.7)^{a}	272.9 (163.7)^{ab}	133 (21.8)^{a}
Undisturbed Topsoil		1.8 (1.2)	7.0 (5.6)^{b}	117.2 (78.0)^{c}	9.8 (5.4)^{c}

PK = Processed Kimberlite

Values reported as Mean (Standard Deviation)

Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.11. Mean soil available nutrients (20 to 30 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	Nitrogen	Phosphorus	Potassium	Sulfur
25/75	Topsoil	16.6 (14.5)^{b}	5.9 (1.2)^{b}	121.0 (79.4)^{b}	36.8 (28.8)^{bc}
50/50	Topsoil	6.9 (2.0)^{b}	4.6 (0.8)^{b}	166.9 (36.6)^{ab}	63.3 (22.8)^{abc}
Gravel	Topsoil	4.1 (1.8)^{b}	3.3 (0.9)^{b}	127.9 (99.1)^{b}	42.4 (58.3)^{bc}
PK	Topsoil	10.6 (12.8)^{b}	5.1 (2.8)^{b}	142.3 (99.0)^{ab}	60.9 (70.0)^{abc}
Till	Topsoil	10.8 (3.8)^{b}	7.3 (3.2)^{b}	100.8 (35.5)^{b}	37.1 (7.9)^{bc}
25/75	None	13.0 (5.3)^{b}	4.1 (1.7)^{b}	178.4 (53.2)^{ab}	80.3 (27.1)^{abc}
50/50	None	14.8 (3.6)^{b}	3.9 (0.7)^{b}	214.0 (29.5)^{ab}	116.9 (19.0)^{ab}
Gravel	None	16.4 (17.3)^{b}	3.0 (1.5)^{b}	34.0 (13.7)^{b}	7.8 (3.7)^{c}
PK	None	4.7 (0.2)^{b}	1.8 (0.7)^{b}	330.3 (46.3)^{a}	128.4 (13.8)^{ab}
Till	None	12.3 (8.5)^{b}	7.1 (0.7)^{b}	64.0 (10.6)^{b}	26.8 (5.7)^{bc}
25/75	Fertilizer	20.7 (13.8)^{b}	4.3 (0.4)^{b}	202.0 (13.3)^{ab}	100.7 (6.9)^{ab}
50/50	Fertilizer	17.6 (13.9)^{b}	4.0 (1.2)^{b}	182.1 (40.1)^{ab}	95.9 (40.2)^{abc}
Gravel	Fertilizer	9.4 (7.1)^{b}	2.4 (0.4)^{b}	35.3 (19.8)^{b}	8.8 (1.8)^{c}
PK	Fertilizer	4.9 (0.8)^{b}	2.1 (0.5)^{b}	339.4 (38.2)^{a}	146.8 (18.2)^{a}
Till	Fertilizer	23.7 (16.7)^{b}	7.5 (1.0)^{b}	68.6 (13.2)^{b}	33.6 (9.9)^{bc}
25/75	Sludge	25.4 (14.5)^{b}	6.3 (1.9)^{b}	152.2 (38.3)^{ab}	69.3 (10.2)^{abc}
PK	Sludge	3.2 (0.7)^{b}	1.8 (0.7)^{b}	343.7 (9.3)^{a}	122.0 (55.2)^{ab}
50/50	Sewage	31.3 (26.6)^{b}	74.9 (45.4)^{b}	189.6 (41.8)^{ab}	70.0 (17.8)^{abc}
Till	Sewage	111.3 (68.5)^{a}	388.5 (99.6)^{a}	179.4 (99.7)^{ab}	61.8 (10.3)^{abc}
Undisturbed Topsoil		1.8 (1.2)^{c}	7.0 (5.6)^{c}	117.2 (78.0)^{b}	9.8 (5.4)^{c}

PK= Processed Kimberlite

Values reported as Mean (Standard Deviation)

Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.12. Mean macronutrients (mg/l) (0 to 10 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	Calcium	Magnesium	Sodium	Potassium
25/75	Topsoil	41.3 (6.1)	46.8 (9.3)^{cd}	19.7 (4.8)^{c}	23.8 (5.2)^{b}
50/50	Topsoil	48.3 (26.2)	79.8 (55.6)^{cd}	31.0 (9.7)^{c}	30.2 (19.0)^{b}
Gravel	Topsoil	32.3 (6.0)	28.3 (35.7)^{cd}	27.0 (9.6)^{c}	24.6 (16.2)^{b}
PK	Topsoil	42.2 (23.8)	33.9 (19.8)^{d}	31.6 (24.2)^{c}	18.0 (6.7)^{b}
Till	Topsoil	29.9 (17.8)	25.8 (15.4)^{d}	33.3 (24.0)^{c}	27.7 (5.9)^{b}
25/75	None	61.4 (12.0)	116.7 (21.7)^{cd}	53.8 (5.2)^{bc}	61.2 (32.6)^{b}
50/50	None	69.9 (25.2)	214.2 (8.6)^{abc}	84.2 (20.4)^{abc}	126.9 (14.6)^{ab}
Gravel	None	62.7 (20.5)	99.9 (10.7)^{d}	37.1 (5.0)^{c}	43.1 (8.4)^{b}
PK	None	83.2 (30.1)	346.1 (167.7)^{a}	108.4 (37.3)^{ab}	221.1 (62.1)^{ab}
Till	None	61.6 (32.5)	41.4 (22.1)^{d}	32.4 (6.3)^{c}	25.1 (4.2)^{b}
25/75	Fertilizer	86.4 (22.9)	218.7 (54.2)^{abc}	82.3 (6.3)^{abc}	101.7 (20.2)^{b}
50/50	Fertilizer	55.3 (15.1)	166.6 (84.0)^{bcd}	63.8 (2.6)^{bc}	101.7 (30.5)^{b}
Gravel	Fertilizer	46.4 (21.8)	53.0 (13.7)^{cd}	25.4 (3.6)^{c}	35.0 (17.0)^{b}
PK	Fertilizer	61.3 (16.7)	295.4 (58.3)^{ab}	100.1 (24.5)^{ab}	210.3 (26.5)^{ab}
Till	Fertilizer	84.1 (29.1)	62.7 (25.2)^{cd}	39.2 (6.3)^{bc}	35.7 (6.4)^{b}
25/75	Sludge	92.1 (24.9)	212.1 (87.4)^{abc}	113.9 (35.7)^{ab}	143.6 (57.6)^{ab}
PK	Sludge	39.1 (0.5)	148.0 (21.7)^{bcd}	104.7 (18.0)^{ab}	186.1 (11.3)^{ab}
50/50	Sewage	57.2 (9.5)	169.2 (50.0)^{bcd}	120.2 (48.3)^{ab}	239.8 (99.2)^{ab}
Till	Sewage	94.6 (38.4)	86.1 (16.5)^{cd}	149.9 (50.9)^{a}	76.2 (305.0)^{a}
Undisturbed Topsoil		9.4 (5.0)	6.0 (2.5)^{cd}	6.8 (5.1)^{c}	18.4 (9.4)^{b}

PK = Processed Kimberlite

Values reported as Mean (Standard Deviation)

Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.13. Mean macronutrients (mg/l) (20 to 30 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	Calcium	Magnesium	Sodium	Potassium
25/75	Topsoil	80.0 (67.5)^{ab}	144.1 (124.0)^{bc}	54.0 (33.5)^{abc}	64.6 (43.0)^{cd}
50/50	Topsoil	77.1 (12.3)^{ab}	189.1 (94.9)^{bc}	69.9 (13.2)^{abc}	88.6 (46.8)^{bcd}
None	Topsoil	42.6 (53.3)^{b}	142.4 (229.4)^{bc}	51.7 (57.3)^{abc}	85.0 (121.3)^{bcd}
PK	Topsoil	101.8 (67.1)^{ab}	196.7 (237.9)^{bc}	63.1 (64.1)^{abc}	112.9 (127.7)^{cd}
Till	Topsoil	100.7 (67.1)^{ab}	123.9 (86.9)^{bc}	60.9 (32.1)^{abc}	50.3 (29.5)^{cd}
25/75	None	121.8 (47.0)^{ab}	344.1 (152.0)^{abc}	85.1 (29.5)^{abc}	125.3 (68.0)^{abcd}
50/50	None	159.6 (35.0)^{ab}	538.2 (39.5)^{a}	138.2 (6.3)^{ac}	203.3 (24.4)^{abcd}
None	None	35.7 (35.5)^{b}	27.5 (14.9)^{c}	34.0 (9.7)^{c}	27.7 (21.2)^{d}
PK	None	119.3 (60.0)^{ab}	493.2 (166.3)^{ab}	128.6 (55.0)^{abc}	262.5 (71.9)^{ab}
Till	None	98.2 (34.0)^{ab}	64.3 (28.4)^{c}	46.0 (11.7)^{bc}	38.6 (2.5)^{cd}
25/75	Fertilizer	217.0 (105.6)^{a}	554.1 (197.3)^{a}	135.7 (34.8)^{ab}	187.7 (48.1)^{cd}
50/50	Fertilizer	114.1 (3.0)^{ab}	347.8 (114.0)^{abc}	98.0 (20.8)^{abc}	134.8 (49.0)^{cd}
None	Fertilizer	37.2 (25.2)^{b}	30.3 (13.1)^{c}	34.4 (13.6)^{c}	25.6 (7.2)^{d}
PK	Fertilizer	136.2 (47.4)^{ab}	588.8 (143.8)^{a}	145.4 (36.1)^{a}	278.0 (50.9)^{a}
Till	Fertilizer	165.8 (54.0)^{ab}	103.6 (52.4)^{c}	47.0 (11.5)^{bc}	53.6 (19.3)^{cd}
25/75	Sludge	134.1 (38.5)^{ab}	277.6 (62.0)^{abc}	76.9 (18.0)^{abc}	108.7 (26.3)^{cd}
PK	Sludge	85.0 (19.6)^{ab}	302.8 (106.3)^{abc}	119.0 (11.8)^{abc}	221.8 (27.7)^{abc}
50/50	Sewage	78.4 (3.6)^{ab}	271.4 (44.7)^{abc}	94.4 (12.8)^{abc}	165.3 (38.5)^{abcd}
Till	Sewage	119.8 (44.9)^{ab}	147.1 (88.4)^{bc}	81.6 (24.3)^{abc}	169.3 (120.0)^{abcd}
Undisturbed Topsoil		9.4 (5.0)^{b}	6.0 (2.5)^{c}	6.8 (5.1)^{c}	18.4 (9.4)^{d}

PK = Processed Kimberlite

Values reported as Mean (Standard Deviation)

Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.14. Mean soil chemistry properties (0 to 10 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	CEC (meq/100 g)	EC (dS/m)	pH	SAR	TC (%)	TOC (%)	IOC (%)	TKN (%)	TC:TKN
25/75	Topsoil	8.9 (1.0)^{ab}	0.6 (0.0)^{d}	6.5 (0.6)^{c}	0.6 (0.2)^{b}	2.3 (1.0)^{bc}	2.2 (1.0)^{b}	0.04 (0.03)^{bc}	0.01 (0.03)^{c}	23:1
50/50	Topsoil	7.9 (0.6)^{ab}	0.9 (0.5)^{cd}	6.9 (0.5)^{bc}	0.7 (0.2)^{b}	1.9 (0.4)^{bc}	1.8 (0.4)^{bc}	0.1 (0.04)^{bc}	0.1 (0.02)^{c}	19:1
None	Topsoil	7.1 (1.3)^{bc}	1.1 (0.2)^{cd}	7.0 (0.5)^{c}	0.7 (0.3)^{b}	2.2 (1.1)^{bc}	2.3 (1.0)^{b}	0.1 (0.1)^{bc}	0.1 (0.04)^{c}	22:1
PK	Topsoil	8.0 (2.5)^{ab}	0.6 (0.3)^{d}	6.1 (0.7)^{c}	0.9 (0.7)^{b}	2.0 (1.2)^{bc}	2.0 (1.1)^{bc}	0.1 (0.03)^{bc}	0.1 (0.02)^{c}	20:1
Till	Topsoil	6.5 (1.3)^{bcd}	1.1 (0.2)^{cd}	6.1 (0.3)^{c}	1.2 (0.7)^{b}	1.8 (0.5)^{bc}	1.8 (0.4)^{b}	0.04 (0.02)^{c}	0.1 (0.02)^{c}	18:1
25/75	None	4.7 (0.8)^{bcd}	1.4 (0.2)^{cd}	8.0 (0.2)^{a}	0.9 (0.1)^{b}	0.3 (0.1)^{cd}	0.2 (0.1)^{d}	0.2 (0.1)^{bc}	0.01 (0.01)^{c}	30:1
50/50	None	7.8 (3.0)^{ab}	2.1 (0.1)^{bcd}	8.1 (0.1)^{a}	1.1 (0.3)^{b}	0.4 (0.04)^{cd}	0.2 (0.1)^{d}	0.3 (0.1)^{bc}	0.0^{c}	40:1
None	None	2.3 (1.5)^{d}	0.7 (0.3)^{d}	7.3 (0.6)^{ab}	1.2 (0.4)^{b}	0.2 (0.1)^{d}	0.2 (0.1)^{d}	0.1 (0.01)^{bc}	0.01 (0.02)^{c}	20:1
PK	None	11.8 (1.1)^{a}	3.0 (1.0)^{bc}	8.2 (0.1)^{a}	1.2 (0.2)^{b}	0.7 (0.04)^{cd}	0.2 (0.2)^{d}	0.5 (0.3)^{a}	0.01 (0.02)^{c}	70:1
Till	None	3.0 (1.1)^{cd}	0.9 (0.3)^{cd}	6.5 (0.4)^{c}	0.9 (0.3)^{b}	0.1 (0.01)^{d}	0.1 (0.1)^{d}	0.04 (0.01)^{bc}	0.01 (0.02)^{c}	10:1
25/75	Fertilizer	5.6 (2.0)^{bcd}	2.1 (0.5)^{bcd}	8.0 (0.1)^{a}	1.1 (0.1)^{b}	0.3 (0.1)^{cd}	0.1 (0.03)^{d}	0.2 (0.03)^{bc}	0.02 (0.02)^{c}	30:1
50/50	Fertilizer	7.6 (2.2)^{abc}	1.7 (0.5)^{bcd}	8.1 (0.2)^{a}	1.0 (0.2)^{b}	0.4 (0.1)^{cd}	0.2 (0.1)^{d}	0.3 (0.1)^{ab}	0.0^{c}	40:1
None	Fertilizer	3.6 (2.1)^{cd}	0.9 (0.3)^{cd}	7.4 (0.4)^{ab}	0.7 (0.1)^{b}	0.2 (0.1)^{cd}	0.1 (0.1)^{d}	0.1 (0.1)^{bc}	0.01 (0.02)^{c}	20:1
PK	Fertilizer	12.3 (1.7)^{a}	2.7 (0.4)^{bcd}	8.1 (0.0)^{a}	1.2 (0.2)^{b}	0.7 (0.1)^{cd}	0.2 (0.2)^{d}	0.6 (0.2)^{a}	0.01 (0.01)^{c}	70:1
Till	Fertilizer	2.6 (0.5)^{cd}	1.3 (0.5)^{cd}	7.0 (0.0)^{bc}	0.8 (0.1)^{b}	0.1 (0.01)^{d}	0.1 (0.1)^{d}	0.05 (0.04)^{bc}	0.01 (0.01)^{c}	10:1
25/75	Sludge	4.0 (0.2)^{bcd}	2.6 (0.7)^{bcd}	7.9 (0.1)^{ab}	1.6 (0.3)^{b}	0.7 (0.3)^{cd}	0.5 (0.3)^{cd}	0.1 (0.04)^{bc}	0.1 (0.03)^{c}	7:1
PK	Sludge	7.5 (1.1)^{abc}	2.0 (0.1)^{bcd}	8.2 (0.1)^{a}	1.7 (0.4)^{b}	1.3 (0.8)^{cd}	1.0 (0.7)^{bcd}	0.3 (0.03)^{ab}	0.1 (0.02)^{c}	13:1
50/50	Sewage	8.8 (1.7)^{ab}	3.6 (1.5)^{b}	7.6 (0.1)^{ab}	1.7 (0.4)^{b}	1.7 (0.3)^{bcd}	1.6 (0.5)^{bcd}	0.2 (0.1)^{bc}	0.2 (0.1)^{b}	9:1
Till	Sewage	9.0 (2.7)^{ab}	7.1 (2.0)^{a}	7.2 (0.1)^{abc}	3.7 (1.5)^{a}	3.5 (0.8)^{b}	3.4 (0.8)^{ab}	0.1 (0.1)^{bc}	0.5 (0.01)^{a}	7:1
Undisturbed Topsoil		18.5 (6.5)^{a}	0.2 (0.1)^{d}	4.5 (0.5)^{d}	0.5 (0.4)^{b}	9.3 (6.5)^{a}	8.7 (7.2)^{a}	0.1 (0.0)^{bc}	0.3 (0.2)^{ab}	13:1

PK = Processed Kimberlite,CEC = cation exchange capacity, EC = electrical conductivity, SAR = sodium adsorption ratio, TC = total carbon, TOC = total organic carbon, IOC = inorganic carbon, TKN = total kjeldahl nitrogen, TC:TKN = C:N ratio

Values reported as Mean (Standard Deviation), Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.15. Mean soil chemistry properties (20 to 30 cm) at the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	CEC (meq/100 g)	EC (dS/m)	pH	SAR	TC (%)	TOC (%)	IOC (%)	TKN (%)
25/75	Topsoil	5.5 (1.7)^{abc}	1.5 (1.0)^{abcd}	7.2 (0.9)^{a}	0.9 (0.4)^{b}	0.4 (0.2)^{abc}	0.3 (0.2)^{b}	0.1 (0.2)^{bc}	0.0
50/50	Topsoil	6.2 (2.1)^{abc}	1.8 (0.6)^{abcd}	7.8 (0.2)^{a}	1.0 (0.1)^{b}	0.6 (0.01)^{ab}	0.3 (0.2)^{b}	0.2 (0.1)^{abc}	0.0
None	Topsoil	3.3 (3.1)$_{c}$	1.4 (1.6)^{bcd}	7.5 (0.6)^{a}	1.2 (0.8)^{ab}	0.6 (0.4)^{ab}	0.5 (0.5)^{b}	0.2 (0.3)^{abc}	0.0
PK	Topsoil	5.1 (3.2)^{abc}	2.1 (1.6)^{abcd}	6.6 (1.2)^{ab}	0.8 (0.4)^{b}	0.4 (0.2)^{abc}	0.2 (0.2)^{b}	0.3 (0.4)^{abc}	0.0
Till	Topsoil	3.9 (1.0)^{c}	1.4 (0.4)^{bcd}	6.5 (0.6)^{ab}	0.9 (0.3)^{b}	0.6 (0.3)^{ab}	0.5 (0.3)^{b}	0.1 (0.1)^{c}	0.0
25/75	None	7.1 (3.1)^{abc}	3.0 (0.9)^{abcd}	7.9 (0.2)^{a}	0.9 (0.1)^{b}	0.4 (0.2)^{abc}	0.1 (0.1)^{b}	0.3 (0.2)^{abc}	0.0
50/50	None	11.2 (4.5)^{ab}	3.9 (0.1)^{ab}	7.9 (0.1)^{a}	1.2 (0.1)^{ab}	0.4 (0.1)^{abc}	0.3 (0.2)^{b}	0.3 (0.1)^{abc}	0.0
None	None	2.2 (1.2)^{c}	0.9 (0.6)^{cd}	7.2 (0.9)^{a}	2.0 (0.1)^{a}	0.1 (0.1)^{c}	0.1 (0.2)^{b}	0.03 (0.01)^{c}	0.0
PK	None	11.3 (1.1)^{ab}	3.8 (1.0)^{abc}	8.1 (0.1)^{a}	1.1 (0.4)^{ab}	0.6 (0.1)^{ab}	0.1 (0.1)^{b}	0.6 (0.3)^{a}	0.0
Till	None	2.9 (0.5)^{c}	1.5 (0.5)^{abcd}	6.3 (0.5)^{ab}	0.9 (0.4)^{b}	0.1 (0.1)^{c}	0.1 (0.1)^{b}	0.1 (0.1)^{c}	0.0
25/75	Fertilizer	7.8 (2.9)^{abc}	4.1 (1.0)^{ab}	7.8 (0.3)^{a}	1.1 (0.1)^{ab}	0.4 (0.2)^{abc}	0.1 (0.2)^{b}	0.2 (0.1)^{abc}	0.0
50/50	Fertilizer	7.6 (1.7)^{abc}	2.9 (0.7)^{abcd}	8.0 (0.2)^{a}	1.0 (0.2)^{b}	0.4 (0.1)^{abc}	0.1 (0.1)^{b}	0.3 (0.1)^{abc}	0.0
None	Fertilizer	0.9 (0.6)^{c}	0.8 (0.4)^{d}	7.5 (0.2)^{a}	1.3 (0.3)^{ab}	0.1 (0.1)^{c}	0.1 (0.1)^{b}	0.1 (0.1)^{c}	0.0
PK	Fertilizer	11.4 (2.5)^{ab}	4.3 (0.8)^{ab}	8.1 (0.1)^{a}	1.2 (0.2)^{ab}	0.6 (0.1)^{ab}	0.2 (0.1)^{b}	0.5 (0.2)^{ab}	0.0
Till	Fertilizer	2.5 (0.7)^{ab}	2.0 (0.7)^{abcd}	6.5 (0.3)^{ab}	0.8 (0.3)^{b}	0.2 (0.1)^{bc}	0.3 (0.3)^{b}	0.03 (0.1)^{c}	0.0
25/75	Sludge	3.4 (0.3)^{c}	2.8 (0.5)^{abcd}	7.8 (0.3)^{a}	0.9 (0.3)^{b}	0.3 (0.1)^{bc}	0.2 (0.1)^{b}	0.1 (0.1)^{bc}	0.0
PK	Sludge	11.8 (0.5)^{a}	2.9 (0.5)^{abcd}	8.4 (0.3)^{a}	1.4 (0.1)^{ab}	0.8 (0.1)^{a}	0.4 (0.1)^{b}	0.4 (0.1)^{abc}	0.0
50/50	Sewage	7.0 (2.4)^{abc}	3.8 (1.6)^{abc}	6.7 (1.9)^{a}	1.1 (0.3)^{b}	0.6 (0.2)^{abc}	0.2 (0.1)^{b}	0.2 (0.1)^{abc}	0.0
Till	Sewage	3.2 (0.4)^{c}	4.4 (1.8)^{a}	7.1 (0.6)^{a}	1.3 (0.2)^{ab}	0.5 (0.1)^{ab}	0.5 (0.2)^{b}	0.1 (0.1)^{c}	0.1
Undisturbed Topsoil		18.5 (6.5)^{ab}	0.2 (0.1)^{d}	4.5 (0.5)^{b}	0.5 (0.4)^{b}	0.5 (0.1)^{ab}	8.7 (7.2)^{a}	0.1 (0.0)^{c}	0.3

PK = Processed Kimberlite,CEC = cation exchange capacity, EC = electrical conductivity, SAR = sodium adsorption ratio, TC = total carbon, TOC = total organic carbon, IOC = inorganic carbon, TKN = total kjeldahl nitrogen, TC:TKN = C:N ratio

Values reported as Mean (Standard Deviation), Different letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.16. Mean heavy metal concentrations (mg/kg) (0 to 10 cm) for the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		Sb, Se	Be, Mo, Ag, Tl	Pb, Sn	Cd	Hg	U	As	Ba	Cr	Co	Cu	Ni	V	Zn
25/75	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	4.0 (0.8)	61.0 (5.3)	36.9 (9.5)	7.0 (2.0)	11.3 (2.3)	68.0 (33.6)	18.7 (0.6)	20.0 (0.0)
50/50	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	4.3 (0.5)	106.7 (24.7)	116.4 (53.1)	18.0 (7.5)	13.3 (2.1)	275.3 (146.8)	22.3 (0.6)	30.0 (0.0)
Gravel	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	3.8 (0.9)	136.0 (62.2)	108.1 (55.0)	25.7 (20.1)	14.7 (1.5)	419.3 (373.6)	24.0 (3.5)	36.7 (5.8)
PK	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	5.3 (1.3)	78.0 (15.6)	53.7 (23.7)	8.3 (2.5)	16.0 (7.5)	68.7 (67.0)	26.0 (6.1)	30.0 (10.0)
Till	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	4.3 (0.5)	94.0 (7.1)	73.4 (22.7)	12.0 (2.8)	14.5 (0.7)	140.5 (48.8)	26.5 (0.7)	30.0 (0.0)
25/75	None	<0.2	<1	<5	<0.5	<0.05	<40	4.4 (1.2)	181.0 (12.5)	151.7 (35.1)	39.0 (12.1)	20.3 (4.7)	616.7 (262.8)	31.3 (7.6)	46.7 (5.8)
50/50	None	<0.2	<1	<5	<0.5	<0.05	<40	3.5 (2.0)	205.0 (89.4)	179.5 (109.4)	41.0 (26.2)	18.3 (1.2)	673.3 (509.4)	29.7 (3.1)	43.3 (5.8)
Gravel	None	<0.2	<1	9.0	<0.5	<0.05	<40	2.5 (1.4)	86.3 (101.9)	79.8 (88.3)	17.3 (22.3)	10.3 (9.2)	268.3 (371.3)	16.6 (16.8)	40.0 (17.3)
PK	None	<0.2	<1	<5	<0.5	<0.05	<40	1.8 (0.6)	281.3 (59.6)	333.3 (21.8)	71.3 (12.1)	17.0 (2.6)	1296.6 (172.1)	25.3 (3.1)	46.7 (5.8)
Till	None	<0.2	<1	7.0	<0.5	<0.05	<40	4.9 (0.9)	117.0 (43.5)	67.1 (40.7)	14.0 (11.3)	19.7 (2.5)	143.3 (205.0)	33.0 (4.4)	70.0 (52.0)
25/75	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	3.5 (1.1)	195.3 (32.6)	215.3 (63.1)	52.7 (15.2)	18.7 (2.3)	903.7 (320.4)	29.0 (3.6)	46.7 (5.8)
50/50	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	2.5 (0.2)	258.3 (37.4)	256.0 (20.7)	61.7 (6.4)	22.0 (6.2)	1080.0 (113.6)	27.3 (2.5)	50.0 (0.0)
Gravel	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	1.8 (0.3)	61.3 (54.4)	48.7 (57.4)	13.7 (17.6)	7.3 (2.1)	221.7 (338.9)	10.7 (2.1)	36.7 (5.8)

Table 2.16. Con't.

Substrate and Amendment	Sb, Se	Be, Mo, Ag,Tl	Pb, Sn	Cd	Hg	U	As	Ba	Cr	Co	Cu	Ni	V	Zn
PK Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	1.9 (0.6)	277.0 (45.4)	305.7 (20.1)	82.7 (6.7)	16.3 (2.5)	1493.3 (106.9)	24.0 (1.0)	46.7 (5.8)
Till Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	4.1 (0.6)	122.0 (53.4)	93.8 (74.4)	16.7 (11.6)	18.7 (4.0)	205.3 (226.6)	30.7 (5.0)	43.3 (5.8)
25/75 Sludge	<0.2	<1	<5	<0.5	<0.05	<40	3.2 (0.7)	256.7 (92.1)	249.0 (52.4)	55.7 (16.1)	17.0 (2.6)	967.7 (289.1)	28.7 (4.0)	46.7 (5.8)
PK Sludge	<0.2	<1	<5	<0.5	<0.05	<40	2.2 (0.7)	335.3 (101.8)	410.3 (71.1)	76.7 (10.7)	17.3 (1.5)	1360.0 (191.6)	28.3 (4.5)	46.7 (5.8)
50/50 Sewage	<0.2	<1	<5	<0.5	<0.05	<40	3.8 (2.0)	178.0 (47.1)	182.0 (56.9)	45.5 (17.1)	22.0 (52.6)	769.0 (296.9)	23.0 (2.2)	157.0 (146.4)
Till Sewage	<0.2	<1	<5	<0.5	<0.05	<40	3.5 (0.5)	164.7 (75.5)	151.0 (93.7)	26.3 (20.2)	90.0 (56.2)	410.0 (399.6)	27.7 (4.2)	250.0 (158.7)
Undisturbed Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	3.7	61.6	27.2	4.6	21.0	15.8	21.0	32.0
Crustal abundance[1]	0.2	2.8	20.0	0.2	0.1	2.7	1.8	600.0	100.0	25.0	55.0	75.0	20.0	70.0
CCME guidelines[2]	20.0	4.0	70.0	1.4	6.6	n/a	12.0	750.0	64.0	40.0	63.0	50.0	130.0	200.0

PK = Processed Kimberlite, Values reported as Mean (Standard Deviation)

[1]Crustal abundance (ppm), [2]CCME guidelines (mg/kg)

Table 2.17. Mean heavy metal concentrations (20 to 30 cm) for the reclamation site at Diavik Diamond Mine, NWT.

Substrate and Amendment		Sb, Se	Be, Mo, Ag, Tl	Pb, Sn	Cd	Hg	U	As	Ba	Cr	Co	Cu	Ni	V	Zn
25/75	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	3.1 (0.5)	127.7 (84.0)	128.2 (105.3)	26.3 (21.5)	13.7 (4.2)	425.7 (391.8)	21.7 (6.7)	36.7 (5.8)
50/50	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	3.7 (2.4)	185.7 (67.0)	213.9 (130.0)	46.0 (28.4)	19.7 (4.7)	770.7 (579.1)	29.7 (7.4)	50.0 (10.0)
Gravel	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	1.7 (1.1)	100.0 (122.6)	99.8 (144.1)	24.0 (35.5)	8.7 (5.1)	392.7 (638.6)	12.3 (8.6)	36.7 (5.8)
PK	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	4.1 (2.1)	179.7 (147.5)	141.2 (173.1)	26.0 (30.3)	18.0 (3.6)	388.7 (607.4)	29.7 (2.1)	40.0 (0.0)
Till	Topsoil	<0.2	<1	<5	<0.5	<0.05	<40	5.6 (1.1)	119.5 (6.4)	73.3 (27.5)	16.0 (8.5)	24.0 (5.7)	177.0 (179.6)	35.5 (3.5)	45.0 (7.1)
25/75	None	<0.2	<1	<5	<0.5	<0.05	<40	2.7 (1.7)	217.3 (69.5)	258.0 (119.2)	60.3 (27.4)	16.0 (1.7)	1062.3 (529.6)	24.7 (2.1)	43.3 (5.8)
50/50	None	<0.2	<1	<5	<0.5	<0.05	<40	2.9 (1.1)	257.3 (37.9)	294.0 (35.9)	67.7 (6.4)	16.7 (0.6)	1236.7 (167.7)	26.6 (0.6)	46.7 (5.8)
Gravel	None	<0.2	<1	<5	<0.5	<0.05	<40	1.1 (0.7)	104.7 (164.8)	128.4 (212.7)	24.0 (39.0)	9.3 (11.8)	404.0 (689.4)	11.0 (14.7)	40.0 (0.0)
PK	None	<0.2	<1	<5	<0.5	<0.05	<40	1.5 (0.4)	226.3 (11.6)	305.0 (42.4)	71.3 (7.6)	14.0 (2.6)	1313.3 (151.8)	21.3 (3.5)	40.0 (0.0)
Till	None	<0.2	<1	<5	<0.5	<0.05	<40	4.4 (1.1)	74.7 (29.0)	37.1 (10.0)	7.0 (2.0)	16.0 (4.6)	22.0 (7.5)	26.3 (9.5)	43.3 (5.8)
25/75	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	2.5 (0.7)	214.0 (24.6)	234.3 (84.1)	59.0 (18.5)	16.0 (1.7)	1048.7 (353.6)	25.0 (2.0)	43.3 (5.8)
50/50	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	2.9 (0.8)	180.7 (13.9)	190.7 (12.6)	44.7 (3.5)	16.0 (2.0)	762.3 (72.2)	25.0 (3.5)	40.0 (0.0)
Gravel	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	1.6 (1.3)	22.3 (23.1)	11.9 (10.8)	2.7 (2.1)	6.0 (5.2)	14.3 (8.1)	7.7 (9.0)	33.3 (5.8)

Table 2.17. Con't.

Substrate and Amendment		Sb, Se	Be, Mo, Ag, Tl	Pb, Sn	Cd	Hg	U	As	Ba	Cr	Co	Cu	Ni	V	Zn
PK	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	2.0 (1.2)	261.3 (65.5)	341.6 (17.2)	75.6 (2.5)	14.3 (2.5)	1393.3 (70.2)	22.3 (4.5)	50.0 (10.0)
Till	Fertilizer	<0.2	<1	<5	<0.5	<0.05	<40	5.1 (1.4)	90.7 (16.3)	44.4 (10.3)	8.3 (1.2)	20.0 (4.4)	38.0 (12.5)	31.0 (6.1)	40.0 (0.0)
25/75	Sludge	<0.2	<1	<5	<0.5	<0.05	<40	2.7 (1.1)	158.3 (54.2)	187.0 (44.5)	41.3 (11.5)	13.3 (4.6)	705.7 (191.4)	23.3 (7.4)	40.0 (10.0)
PK	Sludge	<0.2	<1	<5	<0.5	<0.05	<40	1.7 (0.1)	281.6 (17.8)	366.7 (16.2)	81.3 (6.7)	15.7 (0.6)	1453.3 (111.5)	29.0 (1.7)	50.0 (0.0)
50/50	Sewage	<0.2	<1	<5	<0.5	<0.05	<40	2.8 (1.6)	195.0 (88.3)	198.0 (106.0)	42.5 (22.4)	20.0 (7.6)	719.0 (418.3)	26.0 (10.0)	50.0 (11.5)
Till	Sewage	<0.2	<1	<5	<0.5	<0.05	<40	3.9 (1.2)	158.3 (77.3)	131.9 (126.5)	28.7 (29.1)	25.6 (11.6)	436.0 (563.9)	30.7 (2.1)	66.7 (30.6)
Undisturbed Topsoil		<0.2	<1	<5	<0.5	<0.05	<40	3.7	61.6	27.2	4.6	21.0	15.8	21.0	32.0
Crustal abundance[1]		0.2	2.8	20.0	0.2	0.1	2.7	1.8	600.0	100.0	25.0	55.0	75.0	20.0	70.0
CCME guidelines[2]		20.0	4.0	70.0	1.4	6.6	n/a	12.0	750.0	64.0	40.0	63.0	50.0	130.0	200.0

PK = Processed Kimberlite, Values reported as Mean (Standard Deviation)

[1]Crustal abundance (ppm), [2]CCME guidelines (mg/kg)

Table 2.18. Plant response to soil treatment (Density and Species Richness) at the reclamation site, July 2006 at Diavik Diamond Mine, NWT.

		Density		Species Richness	
Substrate	**Amendment**	**Spring**	**Fall**	**Spring**	**Fall**
25/75	Topsoil	38.3	28.2^{ab}	9.3	9.7^{abc}
50/50	Topsoil	64.0	71.3^{ab}	13.7	11.7^{ab}
Gravel	Topsoil	85.7	133.7^{ab}	13.7	13.3^{a}
PK	Topsoil	86.7	151.8^{a}	11.7	12.0^{abc}
Till	Topsoil	88.7	57.7^{ab}	10.7	13.7^{ab}
25/75	None	38.3	31.7^{ab}	7.3	8.3^{bc}
50/50	None	42.3	48.3^{ab}	9.7	10.0^{abc}
Gravel	None	88.3	64.7^{ab}	12.3	14.7^{abc}
PK	None	9.0	5.0^{b}	4.7	2.7^{abc}
Till	None	31.7	26.3^{ab}	9.3	7.0^{abc}
25/75	Fertilizer	38.0	33.0^{ab}	9.0	8.3^{c}
50/50	Fertilizer	67.3	42.7^{ab}	11.7	9.7^{abc}
Gravel	Fertilizer	128.7	80.7^{ab}	13.3	11.7^{abc}
PK	Fertilizer	93.3	16.7^{b}	8.7	6.3^{abc}
Till	Fertilizer	76.7	72.3^{ab}	11.3	11.0^{abc}
25/75	Sludge	105.0	n/a	9.0	n/a
PK	Sludge	64.0	n/a	7.7	n/a
50/50	Sewage	13.0	40.3^{ab}	6.3	12.0^{abc}
Till	Sewage	42.0	n/a	11.7	n/a

PK = Processed Kimberlite
Different lower case letters within columns denote statistically significant differences at $p \leq 0.05$

Table 2.19. Grass species response (density) to soil treatments at the reclamation site, July 2006 at Diavik Diamond Mine, NWT.

		Cal. can.		Festuca rubra		Festuca saximon.		Agrop. pauci.		Agrop. viol.		Arcta. latifolia		Agrostis scabra		Puccin. nuttal.		Desch. caesp.		Poa glauca		Poa alpina	
Substrate	Amendment	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
25/75	Topsoil	0.3	1.3		0.7	2.3	3.3	4.7	1.7	5.7	8.3	2.3		4.0				0.7	0.3	13.3	7.3	0.7	
50/50	Topsoil	1.3	1.3	0.7		1.7	13.0	1.7	6.0	15.0	17.0	2.0	1.3	1.7	1.0	0.3	3.0	2.3	1.0	22.3	21.3	2.0	
Gravel	Topsoil	2.3	2.3	1.0		13.0	28.7	1.0	6.0	1.7	22.3	3.3	2.0	4.7	5.7			4.3	3.7	25.3	52.3	9.0	3.0
PK	Topsoil	1.0	1.3	1.3	0.3	3.0	25.3	11.3	13.3	21.0	27.0	1.0	7.7	6.0	3.7	0.7	1.3	0.7	3.0	32.3	43.0	5.7	4.3
Till	Topsoil	2.3	2.7	0.3	0.3	6.3	11.0	3.3		21.3	8.7	1.3	2.0	5.3	2.3			3.0	1.0	3.0	12.7	9.3	2.3
25/75	None				0.3	2.3	1.7	5.0	3.7	13.3	8.0			2.0	2.0					14.3	6.3	1.0	3.7
50/50	None					5.0	7.0	2.7		11.3	16.3	1.3	1.3	1.7	1.7			0.7		15.3	14.3	1.3	0.7
Gravel	None	2.0		3.3		2.7	25.3	9.0	4.0	3.0	1.7	1.0	1.3	7.3	1.7	1.0	0.3	7.3	2.3	24.3	18.3	3.0	1.7
PK	None					0.7				1.7	2.7			0.7	0.3					3.3		0.3	
Till	None			0.3	0.3	3.3	8.7	1.0	0.3	1.7	6.7	0.3	1.7					1.0	0.3	7.0	5.3	1.7	
25/75	Fertilizer	2.7		3.0		2.7	9.7	1.3	3.0	8.7	7.0	0.7		3.3	0.3	0.3		0.7		11.3	7.3	1.7	1.0
50/50	Fertilizer			0.7	0.7	3.0	11.0	1.0	2.7	18.7	8.3	4.7	1.0	5.3	2.3			2.3	0.7	16.3	1.3	7.0	1.3
Gravel	Fertilizer	1.3	16.7	4.3		26.3	16.3	2.3	2.3	19.7	6.7	4.3	5.7	12.3	1.3	0.7		7.3	5.7	27.7	13.3	13.3	3.7
PK	Fertilizer	2.7		1.7		4.0	0.7	0.3		23.0	8.3			8.0	0.3			2.7	0.3	27.3	1.7	13.0	
Till	Fertilizer	5.0	1.0	0.7		8.3	13.7	0.3	1.7	22.7	29.3	3.0	1.3	4.0	2.0			3.7	1.3	16.3	13.0	5.7	1.7
25/75	Sludge	3.0	n/a		n/a	32.0	n/a	2.3	n/a	17.3	n/a	1.7	n/a	4.7	n/a		n/a	1.0	n/a	37.3	n/a	1.3	n/a
PK	Sludge		n/a		n/a	0.3	n/a	5.7	n/a	12.7	n/a		n/a	6.0	n/a		n/a		n/a	1.0	n/a		n/a
50/50	Sewage	0.3	1.3	0.3		0.3	3.0	1.0	2.0	4.3	17.0	0.7	0.7		1.3		0.3	0.7	0.7	5.0	8.3	0.3	
Till	Sewage	1.7	n/a		n/a	1.7	n/a	0.3	n/a	13.3	n/a	4.0	n/a	2.3	n/a		n/a		n/a	12.3	n/a	1.0	n/a

PK = Processed Kimberlite, S = Spring seeded treatments, F = Fall seeded treatments, Cala. Can. = Calamagrostis canadensis, Festuca saximon. = Festuca saximontana, Agrop. pauci. = Agropyron pauciflorum, Agrop. viol. = Agropyron violaceum, Arcta. latifolia = Arctagrostis latifolia, Puccin. nattal. = Puccinellia nuttalliana, Desch. caesp. = Deschampsia caespitosa

Table 2.20. Forb species response (total density) to soil treatments at the reclamation site, July 2006 at Diavik Diamond Mine, NWT.

		Oxytopis splendens		Oxytropis deflexa		Oxytropis campestris		Hedysarum mackenzii		Hedysarum alpinum		Birch		Epilobium latifolium		Seed Bank Establishment	
Substrate	Amendment	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
25/75	Topsoil	0.3		1.0	0.8	0.3	0.3	1.0	3.0			1.0				0.7	1.0
50/50	Topsoil		0.7		0.7	0.3	0.7	2.7	2.3	0.7	2.0					0.3	
Gravel	Topsoil	0.7	0.3	1.0	1.7	0.3	0.3	5.0	4.0	0.7			0.3			3.3	1.0
PK	Topsoil	0.3	0.7		3.0		0.5	1.7	11.3	0.3						0.3	5.3
Till	Topsoil		0.7	1.0	0.7	0.3	0.3	3.0	3.3	0.3	0.7	1.3	0.3		0.3		8.3
25/75	None				0.3	0.3	0.7		4.3		0.3						0.3
50/50	None		0.7		0.3		0.7	2.3	2.7					0.7	0.3		2.3
Gravel	None		0.3	0.7	0.7		1.3	3.7	3.0	1.0						1.0	2.7
PK	None	0.3	0.3			0.3	0.3	1.0	0.7		0.3					0.7	0.3
Till	None	0.3			0.3	0.3	0.3	1.3	1.0							4.3	1.3
25/75	Fertilizer						0.3	1.7	3.3								1.0
50/50	Fertilizer	0.7	1.0	0.3	0.7		0.3	6.7	2.0	0.3					0.3	0.3	
Gravel	Fertilizer		0.3	2.0	0.3		0.3	2.7	3.3	1.3				3.0			4.7
PK	Fertilizer	1.3	2.0	1.3	1.0	2.0		5.0	1.7	0.3	0.7					0.7	
Till	Fertilizer			1.0	0.3			3.0	0.3	1.3				1.7	0.3		6.3
25/75	Sludge		n/a	0.7	n/a		n/a	3.7	n/a		n/a		n/a		n/a		n/a
PK	Sludge	1.0	n/a	1.3	n/a	0.3	n/a	6.0	n/a	1.0	n/a		n/a		n/a	28.7	n/a
50/50	Sewage		0.7		1.3		0.3		3.0		0.3						
Till	Sewage	1.7	n/a	1.0	n/a		n/a	2.3	n/a	0.3	n/a		n/a		n/a		n/a

PK = Processed Kimberlite, S = Spring seeded treatments, F = Fall seeded treatments

Table 2.21. Seed mix response to treatment (density) at the reclamation site, July 2006 at Diavik Diamond Mine, NWT.

Substrate	Amendment	Grasses		G-A		Forbs		Adaptable		Esker		No Seed		Heath		Wet Tundra		Birch	
		S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
25/75	Topsoil	1.7	1.3	7.7	2.3	1	1.3	3.7	8.7	5	4			7.7	5.3	9.3	3	0.3	0.8
50/50	Topsoil	7.7	5.7	3.3	15	1.3	1.7	13.3	8	16.3	1.3	1.7		7.3	1.3	5	8	0.7	1.7
Gravel	Topsoil	13.3	1	9.7	37	3.3	2.3	15.3	16	16	21.3	0.7	0.7	1.3	16.7	11.7	23	1	0.3
PK	Topsoil	15.7	44.7	13.7	2.7	0.3	5.7	11	26.7	2	27.2	0.3	0.7	13.3	12	9.7	1	0.3	1.3
Till	Topsoil	18.7	16.3	12	16.3	2	3.7	12	2.7	16.3	4	0.3	0.3	15	4	8.7	7.7		1
25/75	None	7.3	8	6	7		2.7	2	2.3	12	6.3			5	2.3	2.7	2	0.3	0.3
50/50	None	6.7	7.3	2.7	6	0.7	0.7	1.7	5	8.7	9.3	0.3		6.7	1.3	2.3	5.7	0.3	
Gravel	None	1.3	7.3	14	2	2.7	0.3	9.7	1.3	15.7	9.3	0.7		12.7	7.3	17.3	7	2	
PK	None	0.3	1	3	1	1	0.7	0.3	0.3	4.3	1.3						0.7		
Till	None	3.3	3.7	4	7	0.7	2	6	0.3	1	3			7	3	0.7	6.3		0.7
25/75	Fertilizer	6.3	3.3	1	8.3	0.3	0.3	2	4.3	5	11.7			8.3	3.3	5	1	0.3	
50/50	Fertilizer	11.3	6	9	9.3	1.7	1.3	7.3	5.7	11.7	8	0.3	1	12.7	6.7	9.3	2.7	2	0.7
Gravel	Fertilizer	17.7	1	27.7	16.3	4.7		14	7.3	18.3	8.3	5.3		12.3	23.7	17.3	1	3	
PK	Fertilizer	13.3	3	15	0.3	5.3	3	12	1.7	21.3	7.3			16.3	1	8.7	0.3	0.3	
Till	Fertilizer	9.3	8	11	2	3	0.7	1.3	4	19.7	1.3	1.3	0.3	9.7	16	6.3	1.7	3	
25/75	Sludge	15	n/a	33.3	n/a	1.3	n/a	16	n/a	2	n/a		n/a	1.7	n/a	3.3	n/a		n/a
PK	Sludge	7	n/a	28.7	n/a	4	n/a	7.3	n/a	7.7	n/a		n/a	6.7	n/a	2.3	n/a		n/a
50/50	Sewage	3.7	7	1	6		1.3	1.7	6	3.3	3			3	7.7	1.3	5		1
Till	Sewage	5	n/a	3.7	n/a	2.3	n/a	8.7	n/a	9	n/a	0.7	n/a	7.3	n/a	1	n/a	1.3	n/a

PK = Processed Kimberlite, S = Spring seeded treatments, F = Fall seeded treatments, G-A = Grasses without Aggressive species mix

Table 2.22. Treatment response to seed mix (density) and season of seeding at the reclamation site, July 2006 at Diavik Diamond Mine, NWT.

Seed Mix	25/75 None		25/75 Sludge		50/50 None		50/50 Topsoil		Gravel None		Gravel Topsoil		Till Fertilizer		Till Topsoil		Till Sewage	
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
Grasses	7.3^{ab}	8.0	15.0^{ab}	n/a	6.7^{ab}	7.3	7.7^{abc}	5.7	10.3^{abc}	7.3	13.3^{ab}	10.0^{ab}	9.3^{b}	8.0^{ab}	18.7^{a}	16.3^{a}	5.0^{abc}	n/a
G-A	6.0^{ab}	7.0	33.3^{a}	n/a	2.7^{ab}	6.0	3.3^{b}	15.0	23.0^{a}	20.0	9.7^{ab}	37.0^{a}	11.0^{ab}	20.0^{ab}	12.0^{ab}	16.3^{a}	3.7^{abc}	n/a
Forbs	0.0^{b}	2.7	1.3^{b}	n/a	0.7^{b}	0.7	1.3^{c}	1.7	2.7^{bc}	0.3	3.3^{b}	2.3^{b}	3.0^{b}	0.7^{ab}	2.0^{ab}	3.7^{ab}	2.3^{abc}	n/a
Adaptable	2.0^{b}	2.3	16.0^{ab}	n/a	10.7^{a}	5.0	13.3^{ab}	8.0	9.7^{bc}	10.3	15.3^{ab}	16.0^{ab}	10.3^{ab}	4.0^{ab}	12.0^{ab}	2.7^{b}	8.7^{ab}	n/a
Esker	12.0^{a}	6.3	20.0^{ab}	n/a	8.7^{ab}	9.3	16.3^{a}	10.3	15.7^{ab}	9.3	25.0^{a}	21.3^{ab}	19.7^{b}	10.3^{ab}	16.3^{ab}	4.0^{ab}	9.0^{a}	n/a
No Seed	0.0^{b}	0.0	0.0^{b}	n/a	0.3^{b}	0.0	1.7^{c}	0.0	0.7^{c}	0.0	0.7^{b}	0.7^{b}	1.3^{b}	0.3^{b}	0.3^{b}	0.3^{b}	0.7^{c}	n/a
Heath	3.0^{b}	2.0	10.0^{ab}	n/a	4.5^{ab}	10.0	8.0^{abc}	9.5	11.0^{abc}	8.0	8.5^{ab}	14.0^{ab}	10.5^{ab}	22.5^{a}	12.5^{ab}	1.5^{ab}	8.5^{abc}	n/a
WT	2.0^{b}	2.0	1.0^{ab}	n/a	1.0^{ab}	1.0	4.0^{ab}	2.0	12.0^{abc}	6.5	9.0^{ab}	14.0^{ab}	6.0^{b}	2.0^{ab}	6.5^{ab}	6.0^{ab}	1.5^{abc}	n/a
Birch	0.5^{b}	0.0	0.0^{b}	n/a	0.0^{b}	0.0	0.0^{c}	0.0	1.5^{bc}	0.0	0.0^{b}	0.0^{b}	2.0^{b}	0.0^{ab}	0.0^{ab}	0.0^{b}	0.0^{c}	n/a
Transplants	4.5^{ab}	0.5	0.0^{b}	n/a	0.0^{b}	0.0	0.5^{c}	9.0	0.5^{c}	0.5	0.0^{b}	0.0^{b}	0.0^{b}	0.0^{ab}	0.0^{ab}	0.0^{b}	0.5^{bc}	n/a

25/75 = 25 Processed Kimberlite / 75 Glacial Till, 50/50 = 50 Processed Kimberlite / 50 Glacial Till S = Spring, F = Fall
Different lower case letters within columns denote significant difference at the 0.05 level
Only treatments with signficant differences are reported in table (i.e. Treatments: 25/75 Fertilizer, 25/75 Topsoil, 50/50 Fertilizer, 50/50 Sewage, Gravel Fertilizer, PK None, PK Fertilizer, PK Topsoil, PK Sludge and Till None had no significant differences among seed mixes)

CHAPTER III. SUMMARY AND FUTURE DIRECTIONS

1.0 RESEARCH SUMMARY

Although arctic ecosystems have been relatively stable for thousands of years, they are easily altered by anthropogenic disturbances (Reynolds and Tenhunen 1996). This susceptibility is due to a number of factors, including a short growing season, low soil and air temperatures, low intensity of radiation, low primary productivity, the presence of permafrost and the extreme sensitivity of vegetative and organic surface layers to any disruption to their physical integrity and thermal regime. In practical terms, low growth rates render tundra ecosystems slower to recover after disturbance, and thus relatively more sensitive to any alteration of natural conditions (Haag 1974).

Successful reclamation of diamond mining disturbances in the Northwest Territories, Canada involves the re-establishment of soil processes such as nutrient and organic matter cycling and native plant communities including a diversity of shrub, grass, forb and bryophyte species. In this reclamation study at the Diavik Diamond mine site, five substrate treatments, five amendment treatments and two seasons of seeding were tested in combination with six native plant species mixes containing various combinations of 11 native grasses and 6 native forbs. The substrates and soil amendments were selected based on previous reclamation research in northern regions and included materials readily available at the mine site. The substrates included fine processed kimberlite (PK), glacial till (Till), PK and Till in a 25/75 mix, PK and Till in a 50/50 mix and no substrate addition (Gravel). The amendments included topsoil, inorganic fertilizer (11-52-0), sewage sludge (Sewage), sludge from the north inlet water treatment facility (Sludge) and no amendment. The seed mixes contained different combinations of 11 native grasses and 6 native forb species.

A direct relationship between soil treatment and plant establishment was found. Soil treatments with loamy sand textures, increased water holding capacity, organic matter and nutrients, decreased pH, sodium adsorption ratio (SAR) and electrical conductivity (EC) and had higher plant densities. Substrate and amendment combinations (treatments) that produced these soil properties included 25/75 Topsoil, 50/50 Topsoil and Till Topsoil. Sewage amended treatments increased water holding capacity, organic matter and nutrients which are beneficial for plant growth, however EC, phosphorus (P), sulfur (S), sodium (Na) and zinc (Zn) concentrations were also increased which may cause plant toxicities. Sludge treatments showed similar results to Sewage in that they were elevated in S, Na, chromium (Cr) and nickel (Ni). Fertilizer treatments had similar results as Topsoil treatments for plant density, however, soil properties such as soil texture and organic matter, which are essential for sustainable plant growth, were unaffected.

By itself, processed kimberlite is an inhospitable medium for plant growth due to low water holding capacity, high pH, potassium (K), S, Na, Cr, Ni, cobalt (Co) and Zn, however, it is effective in combination with glacial till. The 25/75 and 50/50 treatments showed no significant differences from each other, and although they were slightly elevated in the same nutrients and metals as the PK, concentrations were not high enough to negatively influence plant growth. Although plant density on gravel substrates with topsoil and fertilizer amendments was not significantly different amongst 5/75, 50/50 or Till treatments it is might not be sustainable due to low water holding capacity and organic matter.

Plant density was highest in the Esker, Grasses, and Grasses without Aggressives spring seeded plots. The high density in these seed mixes was due to the presence of grasses *Festuca saximontana* (Rybd.) (Rocky mountain fescue), *Agropyron violaceum* (Hornem.) (Alpine wheatgreass) and *Poa glauca* (Vahl) (Glaucous bluegrass), which showed the highest densities for all treatments. Other grass species that performed well included *Agrostis scabra* (Wild.) (Tickle grass), *Agropyron pauciflorum* ((Schwien) Hitchc.) (Slender wheatgrass), *Poa alpina* (L.) (Alpine bluegrass), *Arctagrostis latifolia* (R.Br) (Rocky mountain fescue) and *Deschampsia caespitosa* ((L.) Beauv.) (Tufted hairgrass). The forb *Hedysarum mackenzii* (Rich.) (Northern hedysarum) had the greatest density for all treatments. The remaining grass and forbs species established in low densities and the remaining seed mixes were not significantly different among treatments.

2.0 RECOMMENDATIONS FOR RECLAMATION AND MONITORING AT DIAVIK DIAMOND MINE

Due to the slow rate of secondary vegetational development in the arctic, the true effects of treatments and seed mixes are only likely to become evident after a long period of time (Forbes and Jefferies 1999). The plant community in this study is in the early stages of development and more time is required to assess the effectiveness of treatments on species density, richness and health. Canopy cover could not be assessed due to low germination rates and poor establishment early in the research. Continued monitoring may yield different results than this initial analysis, therefore, the following recommendations should be considered.

- Continue to monitor the plant community for species density, richness, health and canopy cover annually, as it is difficult to assess vegetation success and treatment effectiveness after only one or two growing seasons and environmental influences will affect the long term sustainability of vegetation. Sustainability will depend on the establishment of new plants from seed produced by seeded species used in reclamation or plants from the surrounding tundra, therefore, plant reproduction and colonization should be monitored.
- Monitor nutrient cycling to determine if natural processes are occurring and organic material is being cycled.
- Monitor C:N ratio and determine if nitrogen is being immobilized or mineralized, if a more suitable ratio develops on substrates with topsoil and no amendment, or if management is necessary.
- Monitor Gravel, Gravel Topsoil and Gravel Fertilizer treatments to determine if vegetation success is sustainable over time.

Reclamation at the mine site is challenging due to the remote location and lack of organic materials, however, consistent with previous research (Reid and Naeth 2005, Stevens 2006) this study has shown that waste materials from the mining process can be used to successfully establish native plant communities.

The purpose of this study was to contribute to the development of appropriate reclamation strategies for Diavik Diamond mine and eliminate substrates, amendments and native plant species that are inappropriate for reclamation at the mine site. The results of this study are listed below.

- Processed kimberlite and glacial till are less conducive to plant establishment alone than in combination.
- There is no significant difference between 25/75 and 50/50 PK and Till mixtures in soil properties or vegetation response, therefore, it would be acceptable to use the one most economically feasible.
- Topsoil provides the most benefits for substrate enhancement and vegetation success and should be used as an amendment whenever possible.
- Sewage is a good source of organic matter and nutrients, however, when applied as raw sewage at the rate in this study, it can be harmful to vegetation success. Rufete et al. (2006) found higher sewage application rates induced long lasting persistence for fecal coliform populations compared to lower rates, which could be a potential source for surface or groundwater contamination.
- Sludge did not enhance plant density and provided no benefits to the soil for nutrients or organic matter, therefore, it is not an effective amendment to be used for reclamation.
- In this short study, spring seeding was more successful than fall therefore seeding should commence in spring whenever possible.
- Substrates with larger boulders and crevices had more microsites which act as wind breaks and are conducive for trapping seeds and moisture, which creates a more suitable environment for seed germination and establishment. Using large rocks and boulders also creates a topography that more closely resembles the undisturbed tundra.
- Seed mixes for reclamation should include grasses species *Festuca saximontana, Agropyron violaceum* and *Poa glauca* and forb species *Hedysarum mackenzii*, as these species performed well on all treatments.

3.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Although this research has provided interesting and practical results for reclamation at diamond mines in Northern regions, it is evident that further research is necessary to confirm if reclamation strategies will be successful and sustainable. Recommendations for future research emanating from the results of this research are listed below.

- Determine and monitor soil temperature and water in an undisturbed soil for comparison with reclamation materials. To fully understand plant temperature and soil water requirements, it is necessary to know the range of soil temperature and water contents that plants are adapted to in an undisturbed environment.
- The majority of accessible topsoil that can be used for reclamation is found in wet tundra environments. The species present in the seed bank of this soil are adapted to moist conditions and are unlikely to germinate and establish in dry upland environments, therefore, the seed bank is less useful as a seed source.
- If topsoil in upland heath tundra environments could be salvaged, the potential for native seed germination and establishment would be enhanced. The increased number of boulders that would be stripped with the soil would be beneficial for increasing microsites and creating a landscape that more closely resembles the undisturbed heath tundra with boulder fields and exposed rock.
- Topsoil stockpiling effects on seeds and vegetative propagules as well as changes in topsoil physical and chemical properties due to stripping should be assessed. Many seeds and vegetative parts die as a result of stripping and stockpiling topsoil for reclamation, therefore, appropriate stripping times and stockpiling size and duration need to be determined.
- Raw sewage applied directly to substrates is an ineffective source of nutrients and organic matter. Mixing sewage with gravel or glacial till to alter the texture, increase available volume, and dilute phosphorus, sulfur and metal contents may be beneficial. Applying sewage at lower rates and incorporation are two additional methods that should be assessed. It would also be beneficial to determine if it is more effective to apply sewage in the fall and not seed into it until the next spring or possibly the spring after depending on fecal coliform counts.
- In this study the total metal content in the soil was analyzed. Total metal content alone is a poor indicator of the environmental risk from metals in soil (Watmough

et al. 2005). Instead, the relative partitioning of metal between soil particles and soil solution should be used to assess the potential leaching of metals and their bioavailability in soils. The dissolved metal pool reflects the soil metal fraction that is susceptible to leaching and could therefore contaminate ground water or surface waters. It would therefore be beneficial to further analyse the dissolved metal pools, particularly nickel and zinc, to determine if they are mobile or available for plant uptake.

- Investigate additional native species such as *Calamagrostis inexpansa* (Northern reedgrass), *Dryas integrifolia, Dryas dummondii* and *Dryas octopetala* beneficial because these species are more common on dry sites.
- Investigate different methods of seeding for wild collected seed. Methods to break dormancy of native seeds should be examined. If suitable methods are determined, it may be beneficial to apply them to the topsoil treatments in an attempt to break the dormancy of seeds in the seed bank.
- Vegetative cuttings and propagules of native shrubs such as *Salix* (Willow) and *Betula* (Birch) species and evergreen creeping species such as *Empetrum nigrum* (Crowberry) and *Vaccinium vitis-idaea* (Bog cranberry) would be useful. The highest percentage of ground cover on heath tundra is from creeping species, thus by determining methods of establishing these species, ground cover could be substantially increased which is beneficial for preventing erosion and initiating establishment of bryophyte species.
- Growing shrub and herbaceous species in a greenhouse and transplanting them in the field could eliminate the risk of poor germination and establishment and give plant species a competitive advantage early in development.

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APPENDIX A. RECLAMATION SPECIES

Festuca rubra (L.)

Festuca rubra var Arctared (Creeping red fescue) is a winter hardy, common, wetland arctic species found throughout the circumpolar arctic region and can provide a maintenance free, long lasting cover (Younkin and Martens 1987). Elliott et al. (1987) found that *Festuca rubra* exhibited the greatest standing biomass and cover of short term biomass production and long term plant cover when seeded at a coal strip mine in Alaska. They credited the long term presence and colonization success of *Festuca rubra* to its tufted to rhizomatous growth form and the litter produced by its basal leaves. *Festuca rubra* is a strong competitor for soil water, mineral nutrients, space and light (Elliot et al. 1987). Reid and Naeth (2005) found *Festuca rubra* produced the best plant growth response on disturbed sites at the Ekati Diamond Mine, NWT. After the initial growing season, it provides excellent erosion control (Younkin and Martens 1987). Due to its competitiveness, invasion of other native plants may be delayed. It may also hinder seedling development due to lack of moisture and light because of the thick root mat and litter layer it produces (Younkin and Martens 1987). *Festuca rubra* is available in many cultivars commercially, and is a good turf stabilizer which makes it a good choice for reclamation. It is available commercially and can be grown on farms outside the arctic (McKendrick 1997a).

Poa glauca (Vahl)

Poa glauca (Tundra bluegrass) is a short to medium height tufted bluegrass commonly growing to a height of 0.5 m (Reid and Naeth 2005). *Poa glauca* is well adapted to dry soils commonly occurring along rivers and on slopes and bluffs (Reid and Naeth 2005). Mitchell (1980a) recommended *Poa glauca* as a significant component of revegetation mixes for disturbed Arctic sites. Reid and Naeth (2005) found that *Poa glauca* performed well on disturbed sites which had both structural and nutrient limitions addressed prior to seeding, and recommends this species for reclamation in Arctic environments. Kershaw and Kershaw (1987) observed *Poa glauca* naturally colonizing disturbed sites along the Dempster Highway, in the northwestern NWT. It is available commercially and can be grown on farms outside the arctic (Mckendrick 1997b).

Poa alpina (L.)

*Poa alpina (*Alpine bluegrass) is a low growing, perennial densely tufted bunchgrass native to Alaska, the Yukon, the Northwest Territories and other Arctic and boreal regions (Helm 1995). *Poa alpina* matures early and produces seed in late June or early July with yields of 224 kg/ha clean seed (Wright 1991). *Poa alpina* is a cultivar developed in Alaska specifically for erosion control in the arctic, subarctic and boreal regions (Wright 1991). *Poa alpina* is highly palatable, therefore may provide winter forage for montane ungulates. It is available commercially but cannot be grown outside the arctic.

Puccinellia nuttalliana (Schult)

Puccinellia nuttalliana (Nuttall's alkali grass) is an erect, perennial bunchgrass with a shallow, fibrous rooting system (Hardy BBT Ltd. 1989). *Puccinellia nuttalliana* is native to Canada and is found in moist to wet environments. The most beneficial aspect of this species for reclamation/restoration is its ability to tolerate salinity and alkalinity. It is available commercially but cannot be grown outside the arctic.

Calamagrostis canadensis (Michx) Beauv.

Calamagrostis canadensis (Bluejoint) is an erect, long lived, rhizomatous perennial species native to the Canadian Arctic. *Calamagrostis canadensis* provides good erosion control in moist and wet soils because of its rhizomatous nature. *Calamagrostis canadensis* grows under a wide variety of environmental conditions, occurring in dense grasslands, in the understory of many forests, on well drained sites and in wetlands (Helm 1995). Although it can provide an excellent cover in riparian areas, its high biomass results in a thick mulch litter layer that can inhibit associated species establishment. Elliott et al. (1987) found that *Calamagrostis canadensis* will naturally invade sites in disturbed arctic environments. It regenerates either from rhizomes or seed following physical disturbance and can hinder native species establishment due to its competitiveness (Helm 1995). *Calamagrostis canadensis* is available from commercial seed suppliers and can be grown outside of the arctic.

Arctagrostis latifolia (R.Br)

Arctagrostis latifolia (Polargrass) is a northern latitude species with a broad circumpolar distribution. It occurs across Alaska, the Yukon and the Northwest Territories in a wide variety of plant communities and often in disturbed areas (Mitchell 1980b). *Arctagrostis latifolia* is a medium to tall grass with relatively wide lax leaves and stout rhizomes. It forms dense clumps of leafy stems in open areas (Mitchell 1980b). Seeds of *Arctagrostis latifolia* are very light and are easily windborne. Seeds mature late in the growing season and remain viable over the winter for early spring germination (Hardy BBT Ltd. 1989). Reid and Naeth (2005) recommend *Arctagrostis latifolia* for use in revegetation mixes in arctic tundra systems where recovery by native species is desired, however caution that it should be included with species better adapted to dry sites. *Arctagrostis latifolia* is available commercially and can be grown on farms outside the arctic (McKendrick 1997a).

Festuca ovina var. saximontana (Rydb)

Festuca ovina var. saximontana (Rocky mountain fescue) is an erect, perennial bunchgrass with a fibrous, shallow rooting system. It is a native, circumpolar species which is intolerant of lead toxicities (Hardy BBT Ltd. 1989). *Festuca ovina var. saximontana* thrives on dry montane slopes, and provides good erosion control for fine and coarse textured soils. It is available commercially and can be grown outside of the arctic.

Agrostis scabra (Wild.)

Agrostis scabra (Tickle grass) is an erect, short lived perennial bunchgrass with a fibrous, shallow rooting system. It is native to most of North America including the Canadian Arctic. *Agrostis scabra* is an excellent colonizer and pioneer of disturbed sites and is tolerant of drought and acid conditions. Elliott et al. (1987) found *Agrostis scabra* to be a successful natural invader of disturbed sites in south central Alaska. *Agrostis scabra* has successfully established on barren, gravelly, stony and rocky slopes with the addition of fertilizer and is adapted to soils with low nutrient status (Hardy BBT Ltd. 1989). Non certified seed is available commercially in small quantities.

***Agropyron pauciflorum* (Schwein) Hitchc.**

Agropyron pauciflorum (Slender wheatgrass) is a tufted bunchgrass ranging in height from 50 to 100 cm (Hardy BBT Ltd. 1989). *Agropyron pauciflorum* is a relatively short lived, cool season perennial species that depends on reseeding to perpetuate a stand. It is a self pollinating species, noted for its high production of seed and superior biomass production. This species is common in the subarctic environments in the Northwest Territories and is adapted to moist conditions. It is noted for good winter tolerance. *Agropyron pauciflorum* is a good colonizer and is reasonably well adapted to disturbance. It is a relatively good competitor in the first two or three years because of its rapid establishment and early seed production (Hardy BBT Ltd. 1989). It is available commercially and can be grown outside the arctic.

***Agropyron violaceum* (Hornem.)**

Agropyron violaceum (Alpine wheatgrass) has small seeds which can remain dormant for long periods of time (Government of Alberta 2004). The seedlings of *Agropyron violaceum* have moderate emergence and good vigor. *Agropyron violaceum* and *Agropyron pauciflorum* have similar properties, and therefore similar benefits for reclamation. Non certified seed is available commercially in small quantities.

***Deschampsia caespitosa* (L.) Beauv.**

Deschampsia caespitosa (Tufted hair grass) is native to the Canadian arctic and subarctic environments (Hardy BBT Ltd. 1989). *Deschampsia caespitosa* is a tall, densely tufted bunchgrass, 20 to 120 cm tall. It is very tolerant of cold and shade, and is found in sloughs, moist draws and wet meadows. *Deschampsia caespitosa* has been observed as a dominant colonizer in many disturbed sites including a river alluvium in northern Alaska, calcareous mine waste minerals and soils with very low pH (Hardy BBT Ltd. 1989). *Deschampsia caespitosa* has a medium rate of growth but has a poor rate of spread. It is considered fair for soil stabilization, and produces considerable ground cover. Helm (1995) found it useful for stabilization and allowing native species establishment when seeded at low rates. *Deschampsia caespitosa* has good competitive ability, however is presumed to be no more than moderately aggressive in relation to other plants (Hardy BBT Ltd. 1989). It is an excellent source of forage for wildlife, especially early in the spring. Non certified seed is available in small quantites commercially.

Hedysarum alpinum (L.)

Hedysarum alpinum (Alpine hedysarum) is a tufted perennial forb with a woody tap root and thick crown. The roots can form nitrogen fixing nodules. It reaches heights of 20 to 75 cm and has several erect stems. *Hedysarum alpinum* is circumpolar in distribution. In North America, *Hedysarum alpinum* grows from Alaska, through Western Canada from British Columbia to Saskatchewan, south to north central Montana, Wyoming and South Dakota (Horvath 2000). *Hedysarum alpinum* grows on shale slides, roadside verges and forest fringes. It often grows near water, but does not grow well in poorly drained, bog type woodland. Densmore and Holmes (1987) chose *Hedysarum alpinum* for assisted revegetation in Alaska because of its ability to develop relatively high cover on disturbed sites with harsh conditions. *Hedysarum alpinum* grows in early successional habitats, with plants flowering in June and July, and seeds ripening in July and August (Horvath 2000). It requires pollination by insects to set seed, and is moderately tolerant of spring and fall frosts. *Hedysarum alpinum* is a promising early successional species for use in reclamation and is recommended for restoration in Alaska, and northern Canada (Horvath 2000). Frequently it colonizes disturbed areas and is adapted to rich, deep soils, but it will survive on rather shallow, rocky soils. It is available in small quantities commercially.

Hedysarum mackenzii (Rich.)

Hedysarum mackenzii (Northern hedysarum) is often mistaken for wild vetch, however *Hedysarum mackenzii* lacks the tendrils at the end of each compound leaf (Government of Alberta 2004). *Hedysarum mackenzii* has erect stems and leaf stalks. The purple, pea flowers occur in loose spikes at the end of a leafless stem. *Hedysarum mackenzii* and *Hedysarum alpium* have similar benefits for reclamation. *Hedysarum mackenzii* is an early successional species which frequently colonizes disturbed areas. It is available in small quantities commercially.

Oxytropis deflexa (Pall.)

Oxytropis deflexa (Reflexed locoweed) is a legume which has tiny seeds that emerge moderately well if seeded into a scarified medium (Government of Alberta 2004). Seedlings have moderate vigour and good growth. *Oxytropis deflexa* blooms in mid summer. *Oxytropis deflexa* is not available commercially, therefore seed must be wild collected.

Oxytropis splendens (Dougl. Ex Hook.)

Oxytropis splendens (Showy locoweed) is a legume which grows up to a foot tall from a heavy tap root and woody root crown. Older plants will have up to a dozen showy purple clusters of flowers. *Oxytropis splendens* can be found on heavily or moderately grazed native prairie and is abundant on highly gravelly moraines. The seedlings of *Oxytropis splendens* have good vigour and growth. The seeds are easily spread by wind because of their small size (Government of Alberta 2004). Non certified seed is available in small quantities commercially.

Epilobium latifolium (L.)

Epilobium latifolium (Broadleaved willowherb) has few to several stems which are decumbent and 10 to 60 cm long (Hardy BBT Ltd. 1989). *Epilobium latifolium* is a native forb in the Northwest Territories. It is a perennial herb which reproduces by seed and by rhizomes. *Epilobium latifolium* can be found in wet places along streams and scree slopes of subalpine and alpine regions (Hardy BBT Ltd. 1989). *Epilobium latifolium* is available from commercial seed suppliers as dwarf fireweed in small quantities.

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APPENDIX B. ADDITIONAL TABLES FOR CHAPTER II

Table B.1. Treatments for the reclamation site at Diavik Diamond Mine, NWT.

Substrate	Amendment	Treatment
25 PK / 75 Till	Topsoil	25/75 Topsoil
50 PK / 50 Till	Topsoil	50/50 Topsoil
Gravel	Topsoil	Gravel Topsoil
PK	Topsoil	PK Topsoil
Till	Topsoil	Till Topsoil
25 PK / 75 Till	None	25/75
50 PK / 50 Till	None	50/50
Gravel	None	Gravel
PK	None	PK
Till	None	Till
25 PK / 75 Till	Fertilizer	25/75 Fertilizer
50 PK / 50 Till	Fertilizer	50/50 Fertilizer
Gravel	Fertilizer	Gravel Fertilizer
PK	Fertilizer	PK Fertilizer
Till	Fertilizer	Till Fertilizer
25 PK / 75 Till	Sludge	25/75 Sludge
PK	Sludge	PK Sludge
50 PK / 50 Till	Sewage	50/50 Sewage
Till	Sewage	Till Sewage

PK = Processed Kimberlite

Table B.2. Amendment rates for the reclamation study at Diavik Diamond Mine, NWT.

		Plot Area (m^2)			Amendment Rate		
Substrate	**Amendment**	**B1**[1]	**B2**[1]	**B3**[1]	**B1**[2]	**B2**[2]	**B3**[2]
25/75	Topsoil	74.9	103.7	118.3	12.0 tons	12.0 tons	12.0 tons
50/50	Topsoil	80.4	97.3	103.4	12.0 tons	12.0 tons	12.0 tons
Gravel	Topsoil	91.2	50.5	89.7	12.0 tons	12.0 tons	12.0 tons
PK	Topsoil	114.3	39.8	115.1	12.0 tons	12.0 tons	12.0 tons
Till	Topsoil	112.5	72.5	108.3	12.0 tons	12.0 tons	12.0 tons
25/75	None	65.3	77.5	100.4	n/a	n/a	n/a
50/50	None	76.6	97.3	108.1	n/a	n/a	n/a
Gravel	None	86.4	50.5	100.1	n/a	n/a	n/a
PK	None	122.6	39.3	118.0	n/a	n/a	n/a
Till	None	110.0	64.5	71.8	n/a	n/a	n/a
25/75	Fertilizer	76.1	103.7	111.8	1440 g	1440 g	1700 g
50/50	Fertilizer	76.6	97.3	88.7	1440 g	1498 g	1700 g
Gravel	Fertilizer	89.1	59.2	85.8	1440 g	844 g	1700 g
PK	Fertilizer	99.1	39.3	113.3	1440 g	576 g	1700 g
Till	Fertilizer	74.6	68.8	51.6	1440 g	980 g	950 g
25/75	Sludge	86.4	131.5	91.2	511 L[3]	511 L[3]	511 L[3]
PK	Sludge	100.3	39.8	124.8	511 L[3]	511 L[3]	511 L[3]
50/50	Sewage	86.4	97.3	93.0	12.0 tons	12.0 tons	12.0 tons
Till	Sewage	114.0	68.8	66.6	12.0 tons	12.0 tons	12.0 tons

PK = Processed Kimberlite

B1 = Block 1, B2 = Block 2, B3 = Block 3

[1] Area includes Spring and Fall plots

[2] Divide amendment rates in half for Spring or Fall plot amendment rates

[3] Three 45 gallon (170 L) barrels were applied to each corresponding Spring plot

Table B.3. Seeding rates for the reclamation study at Diavik Diamond Mine, NWT.

Species	Seed Mix	Plants/ m^{2*}	Seeds/ m^2	Seeds/ plot
Agropyron pauciflorum	Grass	4.55	20	100
Agrostis scabra	Grass	4.55	20	100
Festuca saximontana	Grass	4.55	20	100
Arctagrostis latifolia	Grass	4.55	20	100
Festuca rubra	Grass	4.55	20	100
Poa alpina	Grass	4.55	20	100
Deschampsia caespitosa	Grass	4.55	20	100
Puccinellia nuttalliana	Grass	4.55	20	100
Poa glauca	Grass	4.55	20	100
Calamagrostis canadensis	Grass	4.55	20	100
Agropyron violaceum	Grass	4.55	20	100
Agrostis scabra	G-A	6.25	23	115
Festuca saximontana	G-A	6.25	23	115
Arctagrostis latifolia	G-A	6.25	23	115
Poa alpina	G-A	6.25	23	115
Deschampsia caespitosa	G-A	6.25	23	115
Puccinellia nuttalliana	G-A	6.25	23	115
Poa glauca	G-A	6.25	23	115
Agropyron violaceum	G-A	6.25	23	115
Epilobium latifolium	Forb	3.60	13	67
Hedysarum alpinum	Forb	3.60	13	67
Hedysarum mackenzii	Forb	3.60	13	67
Oxytropis splendens	Forb	1.70	6	28
Oxytropis deflexa	Forb	3.60	13	64
Festuca rubra	Adapt	8.00	30	150
Festuca saximontana	Adapt	8.00	30	150
Arctagrostis latifolia	Adapt	8.00	30	150
Poa glauca	Adapt	8.00	30	150
Hedysarum mackenzii	Adapt	8.00	30	150
Deschampsia caespitosa	Adapt	8.00	30	150

Table B.3. Con't.

Species	Seed Mix	Plants/ m^{2*}	Seeds/ m^2	Seeds/ plot
Poa glauca	Esker	10.00	36	180
Agropyron violaceum	Esker	10.00	36	180
Poa alpina	Esker	10.00	36	180
Festuca saximontana	Esker	10.00	36	180
Oxytropis campestris	Esker	8.33	31	155
Epilobium latifolium	Esker	10.00	36	180
Betula glandulosa	Birch	10.00	40	200
Deschampsia caespitosa	WT	8.00	30	150
Agrostis scabra	WT	8.00	30	150
Puccinellia nuttalliana	WT	8.00	30	150
Calamagrostis canadensis	WT	8.00	30	150
Arctagrostis latifolia	WT	8.00	30	150
Agropyron pauciforum	WT	8.00	30	150
Arctagrostis latifolia	Heath	10.00	36	180
Calamagrostis canadensis	Heath	10.00	36	180
Poa alpina	Heath	10.00	36	180
Agropyron violaceum	Heath	10.00	36	180
Oxytropis splendens	Heath	1.70	6	28

*Seeding rates based on 50 plants/m^2, except for the forb mix which was limited by available seed, therefore was based on 25 plants/m^2

Table B.4. Fecal coliform analysis at the reclamation site at Diavik Diamond Mine, NWT.

		Fecal Coliforms (MPN/g)	
Block	**Substrate**	**0 to 10 cm**	**20 to 30 cm**
1	50/50	<3	<3
1	50/50	<3	<3
1	50/50	>1100	>1100
1	Till	>1100	460
1	Till	460	75
1	Till	1100	240
2	50/50	23	43
2	50/50	460	460
2	50/50	210	1100
2	Till	<3	<3
2	Till	<3	<3
2	Till	4	4
3	50/50	>1100	93
3	50/50	>1100	>1100
3	50/50	240	>1100
3	Till	93	93
3	Till	1100	>1100
3	Till	>1100	>1100

PK = Processed Kimberlite

Table B.5. Soil temperature (°C) for soil treatments during the winter season at Diavik Diamond Mine, NWT.

		Sept 2004-May 2005 (0-10 cm)			Sept 2004-May 2005 (20-30 cm)			Sept 2005-May 2006 (0-10 cm)			Oct 2005-May 2006 (20-30 cm)		
Substrate	Amendment	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	-9.2	11.5	-23.7	-14.8	3.1	-28.7	-7.8	15.9	-19.1	-7.0	10.4	-14.6
50/50	Topsoil	-13.4	15.5	-29.3	-13.4	8.4	-28.5	-8.4	20.5	-19.0	-7.5	10.3	-18.0
Gravel	Topsoil	-7.4	10.1	-19.0	-6.3	6.6	-15.6	-9.3	13.4	-23.4	-6.4	9.7	-14.9
PK	Topsoil	-13.9	17.7	-29.8	-12.6	9.8	-27.5	-8.7	15.3	-24.1	-8.3	9.9	-20.3
Till	Topsoil	-15.3	4.1	-28.8	-6.6	6.5	-16.4	-10.8	14.7	-27.0	-8.0	10.0	-19.8
25/75	None	-11.4	5.8	-20.0	-10.5	4.7	-17.5	-7.8	14.2	-22.6	-6.3	11.2	-15.8
50/50	None	-7.8	14.1	-19.3	-8.2	10.3	-20.1	-7.5	13.0	-22.1	3.5	10.5	-19.4
Gravel	None	-15.5	5.8	-30.0	-13.7	10.8	-28.2	-11.8	13.6	-30.4	-7.1	10.3	-18.6
PK	None	-12.7	6.2	-27.6	-9.6	5.1	-23.5	-10.8	13.8	-30.1	-8.7	12.4	-22.5
Till	None	-8.3	13.7	-21.4	-12.3	14.9	-28.7	-4.3	12.8	-28.7	-8.9	11.6	-21.5
25/75	Fertilizer	-8.8	22.5	-30.3	-10.6	11.6	-28.5	-11.1	17.6	-29.1	-11.1	17.1	-21.8
50/50	Fertilizer	-11.4	15.7	-28.1	-13.0	5.0	-27.3	-11.2	13.6	-28.5	-11.0	10.4	-26.0
Gravel	Fertilizer	-7.4	9.1	-17.9	-10.0	13.4	-24.8	-7.2	11.9	-15.6	-10.1	13.4	-21.3
PK	Fertilizer	-11.8	9.1	-26.8	-12.1	10.9	-28.2	-11.2	14.5	-29.9	-8.5	12.7	-22.5
Till	Fertilizer	-8.7	10.7	-22.6	-13.8	11.6	-29.6	-8.7	12.8	-22.8	-8.2	11.9	-21.4
25/75	Sludge	n/a	n/a	n/a	n/a	n/a	n/a	-6.9	12.3	-18.5	-11.1	10.2	-26.2
PK	Sludge	n/a	n/a	n/a	n/a	n/a	n/a	-11.4	14.0	-30.7	-8.4	6.1	-20.2
50/50	Sewage	-5.9	5.3	-18.0	-10.0	6.8	-21.3	-10.8	14.2	-26.2	-10.7	10.1	-24.5
Till	Sewage	n/a	n/a	n/a	n/a	n/a	n/a	-6.2	12.5	-15.5	-8.4	9.8	-17.7
Overall Mean		-10.6	11.0	-24.5	-11.1	8.7	-24.7	-9.0	14.2	-24.4	-8.0	10.9	-20.4

PK = Processed Kimberlite

Table B.6. Soil moisture (m^3/m^3) for the winter season at Diavik Diamond Mine, NWT.

		Sept 2004-May 2005 (0 to 10 cm)			Sept 2004 -May 2005 (20 to 30 cm)			Sept 2005-May 2006 (0 to 10 cm)			Oct 2005-May 2006 (20 to 30 cm)		
Substrate	Amendment	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
25/75	Topsoil	-0.01	0.11	-0.06	0.01	0.14	-0.04	0.07	0.16	0.05	0.06	0.11	0.05
50/50	Topsoil	-0.01	0.11	-0.03	0.01	0.18	-0.01	0.00	0.10	0.00	-0.07	0.11	-0.11
Gravel	Topsoil	-0.09	0.16	-0.12	-0.03	0.12	-0.04	-0.01	0.07	-0.02	-0.03	0.05	-0.03
PK	Topsoil	-0.01	0.11	-0.02	0.03	0.16	-0.04	0.02	0.15	0.01	0.02	0.07	0.01
Till	Topsoil	0.00	0.18	-0.01	0.02	0.24	0.00	0.01	0.10	0.00	0.03	0.13	0.00
25/75	None	0.00	0.10	-0.02	0.00	0.08	-0.02	0.03	0.16	0.03	0.00	0.26	-0.01
50/50	None	0.03	0.13	0.01	0.03	0.16	0.01	0.05	0.10	0.04	0.02	0.12	0.02
Gravel	None	-0.03	0.07	-0.04	-0.04	0.14	-0.05	0.01	0.08	-0.01	-0.13	0.01	-0.04
PK	None	0.04	0.16	0.02	0.04	0.14	0.01	0.05	0.13	0.05	0.16	0.10	0.02
Till	None	-0.03	0.13	-0.05	-0.02	0.12	-0.04	0.01	0.13	-0.01	-0.02	0.09	-0.03
25/75	Fertilizer	0.03	0.16	0.00	0.04	0.15	0.01	0.02	0.12	0.02	0.01	0.10	-0.01
50/50	Fertilizer	0.01	0.10	-0.01	0.00	0.09	-0.02	0.03	0.08	0.03	0.02	0.09	0.01
Gravel	Fertilizer	-0.01	0.08	-0.02	-0.02	0.11	-0.04	0.01	0.08	-0.01	0.01	0.04	-0.02
PK	Fertilizer	0.05	0.17	0.02	0.04	0.60	0.02	0.05	0.12	0.05	0.03	0.11	0.02
Till	Fertilizer	-0.03	0.06	-0.04	-0.02	0.06	-0.02	0.01	0.18	0.00	-0.01	0.07	-0.03
25/75	Sludge	n/a	n/a	n/a	n/a	n/a	n/a	0.01	0.22	0.01	0.02	0.22	0.01
PK	Sludge	n/a	n/a	n/a	n/a	n/a	n/a	0.05	0.12	0.10	0.03	0.09	0.02
50/50	Sewage	0.01	0.21	-0.01	0.00	0.19	-0.10	0.35	0.17	0.03	-0.04	0.11	-0.09
Till	Sewage	n/a	n/a	n/a	n/a	n/a	n/a	0.03	0.18	0.03	0.02	0.17	-0.09
Overall Mean		0.00	0.13	-0.02	0.01	0.17	-0.02	0.04	0.13	0.02	0.01	0.11	-0.02

PK = Processed Kimberlite